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Bioresource Technology Reports An Innovative Thermal Composter to Accelerate Food Waste Decomposition at the Household Level --Manuscript Draft--

Manuscript Number:	BITEB-D-22-00611R1				
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Keywords:	food waste; active phase; rapid composter; thermal composter				
Corresponding Author:	Badrus Zaman				
	INDONESIA				
First Author:	Badrus Zaman				
Order of Authors:	Badrus Zaman				
	Nurandani Hardyanti				
	Purwono Purwono				
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Abstract:	An innovative, portable thermal composter was developed to accelerate the decomposition of food waste at household. The study aimed to evaluate the performance of the composter by assessing the quality of the compost produced. Food waste was chopped, mixed, stirred at 80 rpm, and heated to ~ 55 °C; thereafter, a bulking agent and stimulated microorganisms were added to the mixture. The composter mixing speed was assessed to calculate the feasible composting time. The results revealed that the active phase of composting process could be completed in a day, producing good quality compost. The pH, electric conductivity, and C/N ratio of the compost was 6.72, 1,148–1,179 μ Scm-1, and 20.38, respectively. The lowest ammonia emissions (i.e., 7.2 g/Nm3) were produced on the sixth day. The total cost required to process 1 kg of food waste in a day was only 2,097.76 Indonesian Rupiah (IDR), highlighting the feasibility of this technology.				

Indonesia, 19th July 2022

Dear Editor-in-Chief of Bioresource Technology Reports Journal

We would like to resubmit a full-length research article entitled "An Innovative Thermal Composter to Accelerate Food Waste Decomposition at the Household Level" by Badrus Zaman, Nurandani Hardyanti, Purwono, & Bimastyaji Surya Ramadan for possible publication in Bioresource Technology Reports Journal. We confirm that this manuscript is original and has not been published elsewhere, nor is it/will it be submitted for publication elsewhere while it is being considered by Bioresource Technology Reports Journal. We also confirm that the authors prepared the manuscript in compliance with the Ethics in Publishing Policy as described in the Guide for Authors.

In this study, we report that an innovative, portable thermal composter was successfully developed. This composter was used to be applied in a household level as home composting. In this study, we found that the composting process could be completed in a single day, producing high quality, mature compost. The pH, electric conductivity, and C/N ratio of the compost was 6.72, 1,148–1,179 μ Scm-1, and 20.38, respectively. The lowest ammonia emissions (i.e., 7.2 g/Nm3) were produced on the sixth day. Finally, the total cost required to process 1 kg of food waste in a single day was only 2,097.76 Indonesian Rupiah (IDR), highlighting the feasibility of this innovative household thermal composter. The number of words in the manuscript is 5,891 words including title page, abstract, and references.

We have no conflicts of interest to disclose. All the authors approve the contents and the submission of this manuscript to Bioresource Technology Reports Journal.

Sincerely, First Author / Corresponding Author

Badrus Zaman

LAMPIRAN 1

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2	Decomposition at the Household Level
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15 ABSTRACT

An innovative, portable thermal composter was developed to accelerate the decomposition of 16 17 food waste at household. The study aimed to evaluate the performance of the composter by 18 assessing the quality of the compost produced. Food waste was chopped, mixed, stirred at 80 rpm, and heated to ~ 55 °C; thereafter, a bulking agent and stimulated microorganisms were 19 20 added to the mixture. The composter mixing speed was assessed to calculate the feasible 21 composting time. The results revealed that the active phase of composting process could be 22 completed in a day, producing good quality compost. The pH, electric conductivity, and C/N ratio of the compost was 6.72, 1,148–1,179 µScm⁻¹, and 20.38, respectively. The lowest 23 ammonia emissions (i.e., 7.2 g/Nm³) were produced on the sixth day. The total cost required 24 25 to process 1 kg of food waste in a day was only 2,097.76 Indonesian Rupiah (IDR), highlighting 26 the feasibility of this technology.

27 Keywords: food waste; active phase; rapid composter; thermal composter

28

29 1. INTRODUCTION

30 Nearly a third of the worldwide food production for human consumption is lost or 31 wasted, accounting for 1.3 billion tons of food per year. The high generation of food waste, representing a global economic loss, which is accounting around \$400 billion per yar (Raj et 32 al., 2022). Among various other types of waste, food waste may generate the highest 33 34 greenhouse gas (GHG) emissions, as it produces an enormous number of contaminants through 35 natural microbial degradation and other indirect processes, including transportation and the use of food processing machinery (Shen et al., 2020). Therefore, preventing food waste at the 36 37 household level, downstream of the food supply chain, is critical in limiting climate change 38 (Parfitt et al., 2010).

39 There are several food waste management strategies, including composting (Cesaro et al., 2019), animal feed (Mo et al., 2018), anaerobic/aerobic digestion (Wainaina et al., 2020), 40 gasification, incineration (You et al., 2016), pyrolysis (Kim et al., 2020), and direct landfill 41 disposal (Goodman-Smith et al., 2020). Composting remains the most widespread solution in 42 43 developing countries, where it treats ~ 90–96% of food waste (Thi et al., 2015). Effective food 44 waste management has been proven to reduce pollutants, odors, and GHG emissions (Wei et 45 al., 2017; Zaman et al., 2021). In addition, composting is a common practice that can be easily implemented in residential households. 46

47 Composting systems at the household and community level have been discussed by Lu and Sidortsov (2019). Household-level composting equipment allows residents to compost 48 49 their food waste, ultimately reducing the volume of domestic waste transported to communal 50 waste processing facilities. There are, however, some challenges facing composting systems at 51 the household level. For example, there is the likelihood of odor emissions during the 52 biodegradation process (Zhou et al., 2020). Moreover, the long processing times involved with 53 composting may lead to residents being unwilling to compost in their homes. The success of 54 household-level composting also depends on the knowledge, capacity, and self-awareness of 55 the residents who manage the household's waste (Fadhullah et al., 2022).

56 There are some techniques presented in previous literatures for reducing the processing time of household composting. For instance, Kalamdhad et al. (2009) created a drum-shaped 57 58 thermophilic composter consisting of chambers with varying temperatures at its chamber. The thermophilic conditions allow for microbial metabolism activation, accelerating the 59 humification rate. The higher the temperature, the greater the microbiological activity will be 60 61 (Ottani et al., 2022). Food waste composting with the addition of microorganisms and thermal 62 elements (0-100 °C) reached the maximum temperature faster (3 days), and the maturation 63 period decreased (4 weeks) (Charkhestani & Kebria, 2022). The composting time of 4 weeks 64 is still contrary to the community's wishes, where they want the composting process to happen 65 right after they throw the waste away in the composting machine. Awasthi et al. (2017) also found that adding multifunctional microorganisms produced better germination test results and 66 67 a composting period of 20 days. A recent study reveals that adding biochar can increase the composting temperature and achieve an advanced thermophilic temperature in a short period 68 69 of time. Thus, making the composting time lasted for only 20 days (Jain et al., 2018). Oktiawan 70 et al. (2018) used a bulking agent at as much as 30% of the total waste to produce mature and 71 stable compost. A processed food waste size of ± 2 mm is ideal for microbes to carry out the 72 humification process and increase composting efficiency. Therefore, continuous aeration and 73 rotation can also reduce the active phase of composting treatment from several weeks to only 74 4.5 days (Alkoaik, 2019). Since the processing time has become a limitation for applicability 75 at the household level, some modifications are still required to increase its efficiency and ensure 76 its feasibility as a household composter.

77 This study developed an innovative household composter with several modifications 78 which fill research gaps and addresses issues presented in previous studies. Furthermore, the 79 composter designed here is simple to use, portable, and operated automatically. Essentially, 80 food waste was stirred, heated, mixed, and decomposed in the composter, allowing active phase 81 of composting to be obtained within a short period. The aim of the study was to demonstrate 82 the utility of a thermal composter prototype in different operational environments. 83 Furthermore, due to the limited research and the importance for further developing food waste management strategies at the household level, the goal of this study was to demonstrate a 84 85 thermal composter that may accelerate the food waste composting process. The focus here was 86 on compost quality and morphology, ammonia (NH₃) gas emissions, and the total operating 87 cost.

88

89 **2. METHODS**

90 This research was conducted in the greenhouse of the Environmental Engineering 91 Department, Faculty of Engineering, Diponegoro University. The thermal composter (see Fig. 92 1) was made of stainless steel (Type 316 austenitic, Indonesia) with dimensions of $60 \text{ cm} \times 30$ $cm \times 55 cm$ (length \times width \times height). The composter frame was made of corrosion-resistant 93 94 galvalume, and its outer layer was made of white and green acrylic. The thermal composter consisted of an inlet chamber, a food waste chopper, a spiral stirrer driven by a motor (0.5 hp, 95 3-phase, 1370 rpm, China), and a heater (12 V). The heater was set to ~ 80 °C to accelerate the 96 97 microbe metabolism and the humification rate. The bottom and sides of the composter were equipped with insulators to reduce heat loss. Finally, activated carbon and a UV lamp were 98 99 attached to the top of the composter to remove odors and microorganisms resulting from the 100 food waste decomposition (Zhou et al., 2020)



101

Fig. 1. Schematic diagram illustrating the design of the thermal composter developed in

103

this study.

105 Food waste was collected from a restaurant in Semarang City using trash bags and 106 transported to the Environmental Laboratory, Faculty of Engineering, Diponegoro University 107 for analysis. Prior to starting the experiment, the composition and physical properties of the 108 food waste were determined; thereafter, the food waste was mixed. The bulking agent used 109 here came from mature and stable compost with a size of 100 mesh. The food waste consisted 110 of various and mixed ingredients such as leftover rice, spinach, chayote, banana peels, 111 vegetable gravy, and many more. First, food waste (500 g per day) was added to the composter 112 inlet and chopped until the food waste particle size was homogenized to ~ 2 cm. Thereafter, 113 the bulking agent was added, accounting for as much as 30% (v/v) of the total food waste. The 114 mixture was then periodically stirred by the spiral stirrer and slowly pushed into the heating chamber, where it was rotated for 1 min every 6 h. Despite the heater being set to 80 °C, the 115 116 mixture's temperature gradually decreased to 28–30 °C while in the cooling compartment or 117 outlet chamber. The composting cycle was carried out for 7 d by adjusting the rotational speed 118 of the spiral stirrer to 80 rpm. Compost was removed via the outlet chamber, with samples 119 collected daily and stored at 4 °C until further analysis.

120 Laboratory tests were conducted to ensure that the compost was actively produced. Compost quality was assessed using the following parameters: (a) moisture content (MC), (b) 121 122 electric conductivity (EC), (c) pH, (d) temperature, (e) total nitrogen (TN), and (f) total organic 123 carbon (TOC). The gravimetric method was used to determine the MC, with the sample being 124 heated to 105 °C using an oven (Memmert UN 50, Germany). The Kjeldahl method was used 125 to determine TN, while TOC was assessed using the Walkley-Black method (UV-Vis 150 126 Spectrophotometer, Thermo Fisher Scientific, USA). The NH₃ emissions were assessed using 127 the indophenol method and a spectrophotometer (Indonesia National Standard - SNI 19-128 7119.1-2005). The compost surface morphology was assessed using scanning electron microscopy (SEM) (Phenom ProX Desktop Scanning Electron Microscope, Thermo Fisher Scientific, USA) at a magnification of 100,000x. To do so, 2 g samples of three compost components (i.e., the bulking agent, food waste, and final compost) were collected and ovendried at 110 °C for 48 h (Memmert, Germany). The sample was ground, sieved through 200 mesh and fixed on a stub (circular metallic plate holder). Thereafter, the sample was sputter coated with gold (Sputter Coater, Quorum Q300T D Plus, UK), ensuring visibility of the morphology.

136 Plant growth tests were conducted to assess the quality of the compost as a plant growth 137 medium. This was done following the procedure described in Nguyen et al. (2020). Mung bean 138 (Vigna radiata) plants sourced from a farm shop (Semarang, Indonesia) were planted in nine 139 polybags of 5 cm \times 15 cm (width \times height) containing compost samples. All plants were treated equally and received the same daily watering. At 7 d, the plants were removed from the 140 141 polybags, and several morphological parameters were measured, including height, weight, root 142 length, and the number of leaves. The plant heights were measured using a ruler, plant weights 143 were measured using an analytical balance (Mettler Toledo, Switzerland), and the germination 144 rates were observed daily. The presence of flies and odors was recorded following the 145 methodology described in Lleó et al. (2013). Finally, an economic evaluation was undertaken, 146 aiming to assess the total costs incurred while operating the thermal composter. The total 147 electrical power required for each component of the composter was converted into Indonesian 148 Rupiah (IDR). Components that required electric power were the chopper, heater, spiral stirrer, 149 and UV lamp. Replacement costs of the activated carbon and bulking agent were also 150 calculated in detail. No labor or transportation costs were incurred.

151

152 3. RESULTS AND DISCUSSION

153 3.1. Moisture Content (MC)

154 The food waste contained an MC of 86.64% (Table 1); this was much higher than the 155 recommended MC (i.e., 40-60%) for favorable microbial growth (Guidoni et al., 2018). 156 However, food waste can produce a significant amount of gas and favors anaerobic processes, 157 which in turn can produce foul odors and contribute to the emission of GHGs (Onwosi et al., 158 2017). The bulking agent contained an MC of 43.16% (Table 1). Despite this, during the 159 composting process, the MC of the food waste and bulking agent mixture decreased drastically 160 to 32.58% after 24 h (Table 1); this was due to the chopping, heating, and stirring that took 161 place in the thermal composter. Water in the food waste evaporated during the heating and 162 thermophilic composting process; this resulted in the MC decreasing to 19.76% at 4 d, while 163 at 5 and 7 d, MCs increased to 23.55% and 23.89%, respectively (Table 1).

The microbes almost became inactive after the MC dropped below 20%; at this stage, the compost products could have been bagged (Zhou et al., 2020). The bulking agent, owing to its compression resistance, helped maintain the porosity and structure of the mixture during composting. Indeed, no leachate was observed, indicating that the addition of the bulking agent influenced the total amount of leachate formed during composting (Guidoni et al., 2018). Finally, the stirring frequency helped maintain the porosity of the mixture and added oxygen to the system.

171

Table 1. Compost quality parameters and growth test results.

Parameter	Units	FW	BA	C-1	C-2	C-3	C-4	C-5	C-6	C-7
MC	%	86.64	43.16	32.58	25.00	25.50	19.76	23.55	24.07	23.89
pН	-	6.63	6.70	6.72	6.32	6.49	6.53	6.72	6.27	7.01
EC	µScm⁻¹	1,591	3,270	891	1,148	1,124	1,435	960	1,170	1,179
Growth test										
Height	cm	0	7.8	25.3	24.8	20.8	21.7	0	18.5	12.4
Weight	g	0	0.2403	0.4512	0.5116	0.4413	0.5308	0	0.5061	0.4843
Root length	cm	0	1.5	5.2	4.5	4.4	4.2	0	2.3	1
Leaf	single leaves	0	2	2	2	2	2	0	2	2

172 FW, food waste; BA, bulking agent; C-1–C-7, daily composting results (i.e., 7 d).

173

174 **3.2.** pH and Temperature

175 The food waste had an original pH of 6.63, while the bulking agent had a pH of 6.70 176 (Table 1). The daily addition of food waste did not significantly alter the mixture's pH, with the mixture at 1 and 7 d having pHs of 6.72 and 7.01, respectively. This pH range is ideal for 177 178 developing bacteria and fungi, thus, contributing to the composting process in producing high-179 quality and mature compost. Yuan & Zhu (2016) stated that the addition of a bulking agent 180 accelerates the increase in pH. Typically, food waste that undergoes natural decomposition 181 produces an acidic pH due to the formation of organic acid (Guidoni et al., 2018). The pH then begins to increase due to the ammonification of organic matter, where organic nitrogen is 182 183 transformed into amide and ammoniacal nitrogen. The formation of NH₃, an alkaline reaction, 184 also increases the pH. Zhou et al. (2020) found that processing food waste using a composter 185 produced weakly acidic pHs during the initial and cooling stages, while an increase in pH was 186 observed during the heating and thermophilic stages. Ultimately, the changes in pH may be 187 attributable to pH imbalances caused by the microbial metabolic activity. Based on the pH 188 value results, compost produced by the thermal composter could be taken during any of the 189 seven composting process days and be used for agricultural purposes.



191

Fig. 2. Graph illustrating the temperature of the thermal composter heater (dashed line),

line).

as well as the compost temperature in the heating (solid line) and outlet chambers (dotted

- 193
- 194

The heater of the thermal composter was set to 80 °C, ensuring consistent thermophilic 195 196 conditions in the heating chamber (Fig. 2). The composting temperature in the heating chamber rose rapidly from 26.3 °C to 52.63 °C within the first 20 min (Fig. 2). Within the same period, 197 198 however, the composting temperature in the outlet chamber only rose from 26.3 °C to 37.44 199 °C (Fig. 2). A temperature of 52.63 °C in the heating chamber was beneficial for thermophilic microbial metabolism. At 7 d, the compost temperatures in the heating and outlet chambers 200 201 were 53.69 °C and 40.69 °C, respectively (Fig. 2), indicating rapid food waste composting in 202 the thermal composter. The thermophilic temperature positively impacts the decomposition 203 rate of food waste so that the composting process can be completed in a day. In addition, this 204 thermophilic temperature decreases food waste's water content, where the initial 86.64% food 205 wastewater content decreases to 32.58% (day 1) and 23.89% (day 7).

- 206
- 207 **3.3.** Electric Conductivity (EC)

The original food waste and bulking agent EC values were 1,591 μ Scm⁻¹ and 3,270 μ Scm⁻¹, respectively. The mixture had an EC value of 0.891 μ Scm⁻¹ after being processed for 1 d in the thermal composter. The observed EC value decrease was due to the chopping, heating, and thermophilic decomposition that occurred in the thermal composter. However, the overall EC value during the composting process did not alter significantly and had a range of 1,148–1,179 μ Scm⁻¹. EC values reflect the salinity of the composting matrix (Onwosi et al., 2017). Furthermore, compost is safe for planting when it displays an EC value < 4,000 μ Scm⁻¹ ¹. In this study, EC values were consistently < 2,000 µScm⁻¹ during the composting process,
and thus, had no impact on biological activity (Mujtaba et al., 2021).

217

218 3.4. Flies and Odor

219 Flies typically land on food waste soon after its disposal. However, in this study, no 220 flies were observed for 7 d, implying that the food waste and the products of its decomposition did not attract flies. Stirring of the mixture every 6 h did not affect the number of flies. A 221 222 previous study found that the capacity of the composter was sufficient to stabilize the organic 223 waste (Blazy et al., 2014). Guidoni et al. (2018) found that flies disappeared after the eleventh day of composting three treatments which varied in their ratio of rice husk to raw fruit and 224 225 vegetables (i.e., 70:30, 50:50, 30:70; v:v). No strong odor was detected during this study. The 226 bulking agent addition allowed the diffusion of gases and it maintained an aerobic composting 227 process. In addition, bulking agents enhanced the inter-particle voids in the composite pile, 228 thereby increasing the air permeability and regulating the humidity of the compost substrate 229 (Yang et al., 2019).



Fig. 3. Graph illustrating ammonia (NH₃) concentrations in ambient air (squares) and NH₃
 emissions during seven days of composting using a thermal composter (circles).

233

234 **3.5.** NH₃ Emissions

235 Emission of NH₃ varies according to the substrate composition, particle sizes, moisture, 236 oxygen distribution, initial temperature gradients, and the overall process conditions (Onwosi et al., 2017). The first day of the composting process produced an NH₃ emission of 4.1 g/Nm³, 237 with an increase to 9.6 g/Nm³ occurring at 2 d (Fig. 3). This increase was likely due to the 238 239 addition of food waste; moreover, the increasing trend continued until 7 d, which saw an NH₃ emission of 21.2 g/Nm³ (Fig. 3). The NH₃ concentrations in ambient air ranged from 1.6–5.4 240 241 g/Nm³, with the lowest concentration (i.e., 1.6 g/Nm³) occurring at 4 d and the highest 242 concentration (i.e., 5.4 g/Nm³) at 6 d (Fig. 3). Overall, the NH₃ concentrations in ambient air 243 did not change significantly (p > 0.05).

244

245 **3.6.** Total Organic Carbon (TOC)

Higher levels of TOC degradation indicate more stable compost (Sharma et al., 2017). 246 247 After 1 d in the thermal composter, the TOC of the compost mixture decreased drastically by 75.94%. The TOC for the remaining days ranged from 77.42–79.94%, lower than the initial 248 249 TOC level (See Fig. 4). The decrease observed here supports Lalremruati & Devi (2021), who 250 stated that the decomposition of vegetable waste is straightforward, owing to it mostly 251 containing cellulose. Liu et al. (2018) reported a decrease in vegetable waste TOC ranging from 252 11.4-32.1%, when using sawdust, cow dung, and inoculum for 40 d. Notably, the TOC 253 decrease observed in this study remained stable (i.e., 77.42–79.94%) throughout the 7-d period, despite the addition of 500 g of food waste per day (Fig. 4). Indeed, these results indicate that 254

the thermal composter is effective in accelerating the degradation of TOC, owing to theintegration of the mixing system, heating parameters, and bulking agent.



Fig. 4. Graph illustrating the level of total organic carbon (TOC) in food waste during seven
 days of composting using a thermal composter.

260

257

261 **3.7.** Total Nitrogen (TN)

262 The initial TN value decreased significantly at 2 and 3 d of the composting process. The 263 decrease in TN is caused by the evaporation of ammonia, and lower pH results in less organic 264 matter mineralization (Wang et al., 2017). As it may see in Fig. 3, the ammonia emission increased from 9.6 to 14.6 g/Nm³. Therefore, the pH values for 2 and 3 d remain at 6.32 and 265 266 6.49, respectively, which are lesser than the pH at 1, 4, 5, and 7 d. Indeed, several studies have 267 attributed the decrease in TN to the volatilization of NH₃, when temperature and pH were more 268 than 45 °C (Cáceres et al., 2018; Zhou et al., 2018). Nguyen et al. (2020) found that TN was 269 influenced by temperature; in addition, the optimal TN was found in experiments that were 270 rotated once per day and exhibited a C/N ratio of 20. Regarding the production of compost 271 from domestic organic waste (Indonesia National Standard - SNI 19-7030-2004), the optimal TN for compost is a minimum of 0.40%. Indeed, the results obtained here confirm that the TN 272

content in the compost collected at 1, 4, 6, and 7 d meet this quality standard. The highest TN
content (i.e., 0.49%) was found on the first day, while the lowest TN content (i.e., 0.28%),
which does not meet the quality standard, was found at 3 d. Ultimately, temperature and the
composition of the compost raw material can affect the TN in the compost.

277

278 3.8. C/N Ratio

279 The C/N ratio is a conventional parameter used to assess the composting process (Zhou et al., 2018). The reduction of the C/N ratio due to the simultaneous consumption of carbon 280 281 and nitrogen organic substrates indicates an effective composting process (Wang et al., 2016), 282 with composts that display a C/N ratio < 20 being considered mature. According to the Ministry 283 of Agriculture of Indonesia Number: 28/Permentan/SR.30/5/2009, organic and biological 284 fertilizers, as well as soil enhancers, typically exhibit C/N ratios within the range of 15–25. The 285 composting process in this study was 500 g of food waste being used as the initial compost raw 286 material; on each of the ensuing days, an additional 500 g of food waste with a typical 287 composition was added. The results reveal that the food waste at 2, 3, and 5 d had C/N ratios > 288 25, ultimately displaying poor composting conditions; whereas at 1, 4, 6, and 7 d, the C/N ratios 289 ranged from 20–25, indicating good compositions. The C/N ratio variation found in this study 290 was ultimately driven by differences in the daily food waste composition and quantity.

291

292 **3.9. SEM Images**

SEM was used as an additional technique to assess micro-changes in the surface morphology of different compost components (See Fig. 5). In SEM, a focused high-energy electron beam is used to scan the surface of a specimen (Oñiguez et al., 2011). The resulting high-quality images provide information about the sample's external morphology (texture) and crystalline structure. Micrographs of food waste samples, compost, and the bulking agent (as

298 provided in supplementary materials) reveal different particle sizes and distributions per unit 299 area, as well as heterogeneity in particle compaction. Moreover, micrographs showed that the 300 compost sample exhibited larger pore diameters and had no particle compaction. However, 301 while the initial food waste displayed small pore diameters, particle compaction was present. 302 Biodegradation has been shown to lead to improved texture and particle compaction (Arora & 303 Kaur, 2019). The same result was shown by Ajmal et al. (2021), where the food waste has 304 tightened microscopic structure compared to the compost product. This result may be due to 305 the microorganism activity, which reduces the particle size and increase the holes of the 306 fermented food waste. Moreover, the surface roughness and irregular pore shapes shown in the 307 compost product may indicate the possibility of microbial degradation during the composting 308 process (Ma et al., 2022).



(a)

(b)

(c)

Fig. 5. Surface morphology of (a) bulking agent, (b) food waste, and (c) compost produced
from thermal composter at 10,000x magnification. The red arrows indicate the distribution of
particle sizes and the circles indicate the pore diameters.

312

313 **3.10.** Growth test

Compost products derived from food waste generally provide improved plant growthconditions. The plant growth tests revealed rapid and consistent daily mung bean growth.

Growth tests using compost taken from six of the seven composting days (i.e., 1–4, 6, and 7 d) as well as the bulking agent alone, resulted in increased plant height and weight (Table 1). Growth tests using the fresh food waste alone, however, did not facilitate any plant growth (Table 1), with the waste beginning to rot at 1 d. Moreover, no plant growth was observed t 5 d (Table 1); this was due to the accumulation of acidic decomposition products. Ultimately, the results presented here agree with the literature that compost from food waste can be used as a plant growth medium (Nguyen et al., 2020).

323

324 **3.11.** Practical Evaluation and Future Research Direction

325 Household food waste composting does not require labor, transport, sorting, or 326 processing fees. Zhou et al. (2020) believe that the in-situ composting system differs from the 327 centralized composting system. The thermal composter used in this study processed 1 kg of 328 food waste per day, using a total electrical power of 1.452 kWh. This total power consists of 329 the shredding unit (i.e., 0.00375 kWh), the spiral stirring unit (i.e., 0.00828 kWh), and the 330 heating unit (i.e., 1.440 kWh). To process 1 kg of food waste in a day, the heating unit required 331 the most power as it operated for 24 h, while the shredding and stirring units operated for only 332 30 and 80 s, respectively. The total cost for operating the thermal composter amounted to 2,097.76 IDR to process 1 kg of food waste in a single day. The total cost of the composter 333 334 developed by Zhou et al. (2020) requires \$0.033 (445.98 IDR) per kg for food waste, but the 335 composting time is longer (four days). Even though the electricity cost is 2,097.76 IDR to 336 process 1 kg of food waste in a day, food waste composting using a thermal composter still get 337 profits from selling the compost product as a fertilizer for 5,000.00 IDR (Paduloh & Rosihan, 338 2021). Moreover, the compost improves soil quality, assists the remediation of contaminated 339 soil and reduces the need for chemical fertilizers. Solar cells can be an alternative AC power source for thermal composter operations. In addition, it is necessary to increase publicacceptance of the thermal composter so that they can use it to treat food waste.

342

343 4. CONCLUSION

344 Thermal composting is considered a straightforward and effective strategy to manage 345 household food waste. In this study, an innovative household thermal composter was developed 346 and its feasibility assessed. Active phase of composting was finished after a single day of treatment, with MC, pH, temperature, EC, TOC, TN, C/N ratios, and SEM images meeting the 347 348 criteria required for high quality compost. Regardless, the compost obtained after a single day was used successfully as a plant growth medium, confirming the compost's low toxicity level. 349 350 Furthermore, the composter was shown to require a small amount of daily electricity to process 351 food waste.

352

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358

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360 Badrus Zaman: Conceptualization, Supervision, Writing-Review & Editing Nurandani

361 Hadiyanti: Validation, Resources Software Purwono: Investigation, Formal Analysis, Project

362 Administration Bimastyaji Surya Ramadan: Writing-Review & Editing, Data Curation

363

364 CONFLICT OF INTEREST

365 The authors declare that there is no conflict of interest exists.

366

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LAMPIRAN 2

No	Comments	Response	Modification			
Rev	iewer 1					
1)	Page 2, lines 31-34; please provide the reference for the statement "Among various other types of waste, food waste may generate the highest greenhouse gas (GHG) emissions, as it produces an enormous number of contaminants through natural microbial degradation and other indirect processes, including transportation and the use of food processing machinery."	We added the references as suggested.	Among various other types of waste, food waste may generate the highest greenhouse gas (GHG) emissions, as it produces an enormous number of contaminants through natural microbial degradation and other indirect processes, including transportation and the use of food processing machinery (Shen et al., 2020). Therefore, preventing food waste at the household level, downstream of the food supply chain, is critical in limiting climate change (Parfitt et al., 2010).			
2)	Page 5, lines 103-104; there is no clear idea on why the food waste considered for composting consisted of only rice, spinach, chayote, and banana peels, whereas the food waste collected from a restaurant usually has many other items in it.	We agreed with your opinion. We realized that there is a mistake here. After careful cross checked, we modified the sentences.	The food waste consisted of various and mixed ingredients such as leftover rice, spinach, chayote, banana peels, vegetable gravy, and many more.			
3)	Page 8, table 1; please check the height of the plant with bulking agent and the EC value of C-1.	The punctuation errors are revised as suggested.	Height should be 7.8 and EC value of C-1 should be 891			
4)	Page 13, lines 251-254; please check the pH values for day 2 and 3 as there is loss of TN when the pH values rises above 7.7 whereas in the table 1 the pH values for day 2 and 3 remain 6.32 and 6.49 respectively, which are lesser than the pH of days 1, 4, 5 and 7.	We made a modification and added some discussion in the mentioned part of the manuscript. We hoped that the discussion can answer reviewer doubt.	The initial TN value decreased significantly at 2 and 3 d of the composting process. The decrease in TN is caused by the evaporation of ammonia, and lower pH results in less organic matter mineralization (Wang et al., 2017). As it may see in Fig. 3, the ammonia emission increased from 9.6 to 14.6 g/Nm ³ . Therefore, the pH values for 2 and 3 d remain at 6.32 and 6.49, respectively, which are lesser than the pH at 1, 4, 5, and 7 d. Indeed, several studies have attributed the decrease in TN to the volatilization of NH ₃ , when temperature and pH were more than			

Response to Reviewer Comments

No	Comments	Response	Modification				
			45 °C (Cáceres et al., 2018; Zhou et				
			al., 2018).				
5)	Page 13, line 272-274; please	We want to clarify that	The composting process in this study				
	elaborate on the different	the food waste has a	was 500 g of food waste being used as				
	composition of the additional	typical composition since	the initial compost raw material; on				
	500 g of food waste added to	we took the food waste	each of the ensuing days, an				
	the initial compost raw	from the same restaurant	additional 500 g of food waste with a				
	material.		typical composition was added.				
6)	Page 15, section 3.11; the	Because there is a	The total cost of the composter				
	economic evaluation section	limitation regarding	developed by Zhou et al. (2020)				
	can be further improved by	number of table and	requires \$0.033 (445.98 IDR) per kg				
	comparing the cost analysis of	figure, we don't add any	for food waste, but the composting				
	the present thermal composter	tables/figures. We added	time is longer (four days). Even				
	to that of the cost analysis of	more discussion to	though the electricity cost is 2,097.76				
	the conventional composters	answer the suggestion of	IDR to process 1 kg of food waste in				
	reported in the previous	reviewer.	a single day, food waste composting				
	literatures.	The economic evaluation	using a thermal composter still get				
		is improved by	profits from selling the compost				
		comparing the composter	product as a fertilizer for 5,000 IDR				
		developed by Zhou et al.	(Paduloh & Rosihan, 2021).				
		(2020) with the current					
		study.					
7)	I think the format of citations	Thank you for your	Included in the manuscript				
·	and referencing are not	suggestion. In the revised	•				
	following the styles needed by	manuscript, we followed					
	this journal. Please check the	journal guidelines here:					
	guidelines.	https://www.elsevier.com					
		/journals/bioresource-					
		technology-reports/2589-					
		014X/guide-for-authors.					
		The changes indicated in					
		red colour.					
8)	The typo-errors need to be	The typo errors are	Table 1:				
	taken care of throughout the	already checked line by	7,8 modified to 7.8				
	manuscript.	line.	0,891 modified to 891				
Revi	iewer 2						
1)	The presented MS entitled	Thank you for your	-				
	"An Innovative Thermal	suggestion. The gaps					
	Composter to Accelerate Food	analysis of the					
	Waste Decomposition at the	manuscript in the					
	Household Level" may be an	introduction section has					
	interesting read to scientific	been improved. The					
	community for food waste	discussion also modified					
	valorization. However, the	to support the novelty of					
	indepth read of the MS	this study.					

No	Comments	Response	Modification			
	showed that MS requires a					
	major critical revision prior to					
	reconsideration for this					
	journal. In general, the					
	research results provided are					
	not well supported with					
	proper discussion. Besides,					
	the author should emphasis he					
	novelty of the statement.	2				
2)	Abstract needs to be redraw,	Do you mean the	An innovative, portable thermal			
	which summarizes the overall	graphical abstract? we	composter was developed to			
	research work and major	revised some words in	accelerate the decomposition of food			
	The authors should follow the	the abstract and graphical	waste at nousenoid. The study aimed			
	The authors should follow the	abstract as suggested.	to evaluate the performance of the			
	information	However, the abstract is	the compost produced. Food wests			
	https://www.elsevier.com/jour	we tried as good and	was chopped mixed stirred at 80			
	nals/bioresource_technology_	compact as possible to	rpm and heated to $\approx 55 ^{\circ}\text{C}$:			
	reports/2589-01/4x/guide-for-	make the abstract	thereafter a bulking agent and			
	authors	readable and summarized	stimulated microorganisms were			
	autions	the major findings	added to the mixture. The composter			
		the major manigs.	mixing speed was assessed to			
			calculate the feasible composting			
			time. The results revealed that the			
			active phase of composting process			
			could be completed in a day.			
			producing good quality compost. The			
			pH, electric conductivity, and C/N			
			ratio of the compost was 6.72, 1,148–			
			$1,179 \ \mu \text{Scm}^{-1}$, and 20.38,			
			respectively. The lowest ammonia			
			emissions (i.e., 7.2 g/Nm ³) were			
			produced on the sixth day. The total			
			cost required to process 1 kg of food			
			waste in a day was only 2,097.76			
			Indonesian Rupiah (IDR),			
			highlighting the feasibility of this			
			technology.			
3)	Highlights should consist of a	The highlights have been	• An innovative portable food waste			
	short collection of bullet	revised accordingly.	thermal composter was sucessfully			
	points that capture the novel		developed			
	results of your research as		• The active phase of composting was			
	well as new methods that were		obtained on a day			
	used during the study. Kindly					
	include some quantitative and					

No	Comments	Response	Modification			
	quantitate finding of the		• The composting process produce			
	research results. Please follow		low ammonia emission (9.6 – 14.6			
	for more information at		g/Nm ³)			
	https://www.elsevier.com/auth		• The composter requires a small			
	ors/tools-and-		amount of energy, around 1.44			
	resources/highlights.		kWh/kg-waste			
			• The produced compost can be a			
			plant medium without passing the			
			curing phase			
	MS with certain latest citations in particular area. For instance, food production for human consumption is lost or wasted, accounting for 1.3 billion tons of food per year data is seems old. Please update it from 2022. For instance, the author may follow https://www.sciencedirect.co m/science/article/pii/ S0960852422008410 article which describes the global release of waste food stream and their potential.	updated as suggested. Some newly published references were added in the whole manuscripts.	 rotarly a unite of the worldwhee root production for human consumption is lost or wasted, accounting for 1.3 billion tons of food per year. The high generation of food waste, representing a global economic loss, which is accounting around \$400 billion per yar (Raj et al., 2022). The decrease in TN is caused by the evaporation of ammonia, and lower pH results in less organic matter mineralization (Wang et al., 2017). Food waste composting does not require labor, transport, sorting, or processing fees. Zhou et al. (2020) believe that the in-situ composting system differs from the centralized composting system. 			
			The total cost of the composter developed by Zhou et al. (2020) requires \$0.033 (445.98 IDR) per kg for food waste, but the composting time is longer (four days). Even though the electricity cost is 2,097.76 IDR to process 1 kg of food waste in a day, food waste composting using a thermal composter still get profits from selling the compost product as a fertilizer for 5,000.00 IDR (Paduloh & Rosihan, 2021).			
5)	aim, and novelty statement	added in the introduction as suggested	in previous literatures for reducing the processing time of household			

No	Comments	Response	Modification			
	should be given in details in		composting. For instance, Kalamdhad			
	the introduction.		et al. (2009) created a drum-shaped			
			thermophilic composter consisting of			
			chambers with varying temperatures			
			at its chamber. The thermophilic			
			conditions allow for microbial			
			metabolism activation, accelerating			
			the humification rate. The higher the			
			temperature, the greater the			
			microbiological activity will be			
			(Ottani et al., 2022). Food waste			
			composting with the addition of			
			microorganisms and thermal elements			
			(0-100 °C) reached the maximum			
			temperature faster (3 days), and the			
			maturation period decreased (4			
			weeks) (Charkhestani & Kebria,			
			2022). The composting time of 4			
			weeks is still contrary to the			
			community's wishes, where they want			
			the composting process to happen			
			right after they throw the waste away			
			in the composting machine. Awasthi			
			et al. (2017) also found that adding			
			multifunctional microorganisms			
			produced better germination test			
			results and a composting period of 20			
			days. A recent study reveals that			
			adding biochar can increase the			
			composting temperature and achieve			
			an advanced thermophilic temperature			
			in a short period of time. Thus,			
			making the composting time lasted			
			for only 20 days (Jain et al., 2018).			
			Oktiawan et al. (2018) used a bulking			
			agent at as much as 30% of the total			
			waste to produce mature and stable			
			compost. A processed food waste size			
			of ± 2 mm is ideal for microbes to			
			carry out the humification process and			
			increase composting efficiency.			
			Therefore, continuous aeration and			
			rotation can also reduce the active			
			phase of composting treatment from			
			several weeks to only 4.5 days			

No	Comments	Response	Modification		
			(Alkoaik, 2019). Since the processing		
			time has become a limitation for		
			applicability at the household level,		
			some modifications are still required		
			to increase its efficiency and ensure		
			its feasibility as a household		
-			composter.		
6)	Line no. 54 to 71 seems	Thank you for your	Line 54 to 71 is moved		
	irrelevant. Please state the	correction. We moved			
	significance of this.	the sentences and			
		rearranged the			
		introduction section to			
7)		make a better flow			
	Methods and material: The	In the methods section,	The heater was set to $\sim 80^{\circ}$ C to		
	aution should mention the	the information	accelerate the inicious metadolisin		
	the MS For instance "the	the miormation.	and the numinication rate		
	heater was set to ~ 80 °C				
	What is exact temperature for				
	the reaction				
8)	SEM results are not	We added some	The same result was shown by Aimal		
0)	satisfactory Please state the	explanations about the	et al (2021) where the food waste		
	significance of SEM analysis	SEM results The	has tightened microscopic structure		
	in particular study.	analysis is also added us	compared to the compost product.		
		suggested.	This result may be due to the		
		2	microorganism activity, which		
			reduces the particle size and increase		
			the holes of the fermented food waste.		
			Moreover, the surface roughness and		
			irregular pore shapes shown in the		
			compost product may indicate the		
			possibility of microbial degradation		
			during the composting process (Ma et		
			al., 2022).		
			Fig. 5 . Surface morphology of (a)		
			bulking agent, (b) food waste, and (c)		
			compost produced from thermal		
			composter at 10,000x magnification.		
			The red arrows indicate the		
			distribution of particle sizes and the		
			circles indicate the pore diameters.		
9)	What author means growth	The growth test is to	"At 7 d, the plants were removed		
	test. What are parameters	ensure that the compost	from the polybags, and several		
		produced from the active	morphological parameters were		

No	Comments	Response	Modification			
	selected to measure the growth terms and what aspect.	phase of composting can be used as plant growth medium or not. The concept of the test is nearly the same with the germination test. However, we followed the methods by Nguyen et al., (2020) where in their research, they mentioned about "vegetable-growth experiments"	measured, including height, weight, root length, and the number of leaves. The plant heights were measured using a ruler, plant weights were measured using an analytical balance (Mettler Toledo, Switzerland), and the germination rates were observed daily."			
10)	Section 3.2, the effect of pH and temperature needs to be clarified. The results are properly discussed in every aspect. Please revise this section.	Thank you for your comments. We added some discussion related to this matter in this section as suggested.	The daily addition of food waste did not significantly alter the mixture's pH, with the mixture at 1 and 7 d having pHs of 6.72 and 7.01, respectively. This pH range is ideal for developing bacteria and fungi, thus, contributing to the composting process in producing high-quality and mature compost. The thermophilic temperature positively impacts the decomposition rate of food waste so that the composting process can be completed in a day. In addition, this thermophilic temperature decreases food waste's water content, where the initial 86.64% food wastewater content decreases to 32.58% (day 1) and 23.89% (day 7).			
	Section 3.11, what parameters the author have selected for economic evaluations. Please include the system boundaries and variable. For instance, water ratio, energy input, feed stock costing, mechanical processing cost etc. Please elaborate in details as the discussion provided seems not sufficient to describe novelty.	We made a modification on the title: 3.11. Practical Evaluation and Future Research Direction The system boundaries are mentioned and discussed briefly. Therefore, the water ratio and other parameter is descriptively explained. We hoped that the	Household food waste composting does not require labor, transport, sorting, or processing fees. Zhou et al. (2020) believe that the in-situ composting system differs from the centralized composting system. The thermal composter used in this study processed 1 kg of food waste per day, using a total electrical power of 1.452 kWh. This total power consists of the shredding unit (i.e., 0.00375 kWh), the spiral stirring unit (i.e., 1.440			

No	Comments	Response	Modification
		additional information	kWh). To process 1 kg of food waste
		can enhance the	in a day, the heating unit required the
		readability and is	most power as it operated for 24 h,
		sufficient to explain the	while the shredding and stirring units
		novelty.	operated for only 30 and 80 s,
			respectively. The total cost for
			operating the thermal composter
			amounted to 2,097.76 IDR to process
			1 kg of food waste in a single day.
			The total cost of the composter
			developed by Zhou et al. (2020)
			requires \$0.033 (445.98 IDR) per kg
			for food waste, but the composting
			time is longer (four days). Even
			though the electricity cost is 2,097.76
			IDR to process 1 kg of food waste in
			a day, food waste composting using a
			thermal composter still get profits
			from selling the compost product as a
			fertilizer for 5,000.00 IDR (Paduloh
			& Rosihan, 2021). Moreover, the
			compost improves soil quality, assists
			the remediation of contaminated soil
			and reduces the need for chemical
			fertilizers. Solar cells can be an
			alternative AC power source for
			thermal composter operations. In
			addition, it is necessary to increase
			public acceptance of the thermal
			composter so that they can use it to
			treat food waste.
10			
12)	Conclusion needs to be revise	Because the limitation of	Moreover, the compost improves soil
	with clear emphasis on the	the number of words in	quality, assists the remediation of
	future application of the	the conclusion section	contaminated soil and reduces the
	current results	(only 100 words), we	need for chemical fertilizers. Solar
		changed the "economic	cells can be an alternative AC power
		evaluation section into	source for thermal composter
		practical evaluation and	operations. In addition, it is necessary
		ruture research direction"	to increase public acceptance of the
		which emphasize the	thermal composter so that they can
		ruture application of the	use it to treat food waste.
E -124	or Comments	current results.	
Lait	or comments		

No	Comments	Response	Modification		
1)	Each highlight must not	We confirm that the	• An innovative portable food waste		
	exceed 85 characters	highlights are not	thermal composter was sucessfully		
	including space.	exceeding 85 characters.	developed		
		We revised the highlights	• The active phase of composting was		
		as reviewer 2 suggested	obtained on a day		
			• The composting process produce		
			low ammonia emission $(9.6 - 14.6)$		
			g/Nm ³)		
			• The composter requires a small		
			kWh/kg wests		
			• The produced compost can be a		
			plant medium without passing the		
			curing phase		
2)	Conclusions must not exceed	We confirm that the	-		
_/	100 words.	conclusion is consisted of			
		98 words.			
3)	Reference format must be	As it is mentioned by	Included in the manuscript		
	correct.	first reviewer, we			
		changed the references			
		format as per journal			
		guideline.			
4)	Maximum number of figures	We confirm that the	-		
	and tables allowed is six.	number of figures and			
		tables in the manuscript			
5)	Sugalementory motorials must	18 0.	CEM recent is many d from the		
3)	supplementary materials must	As it is mentioned that SEM cannot be placed in	SEW result is moved from the		
	manuscript as Table S1 or	supplementary materials	supplementary mes to the manuscript.		
	Figure S1 (must be 'as given	so we replaced the SFM			
	in supplementary material')	is moved to the			
	- No abbreviations in title.	manuscript			
	- No single column tables	r in the second s			
	(such as characterisation of				
	biomass),				
	- No single parameter figure,				
	- No routine spectra, etc such				
	as SEM, X-ray, FTIR, etc,				
	- No photos of simple				
	equipment or lab set-up,				
	- NO TABLE REPORTING				
	OTHERS RESULTS AND				
	OWN RESULTS (such tables				
	are only in reviews)				



HIGHLIGHTS

•_-

- An innovative portable food waste thermal composter was sucessfully developed
- <u>The Mature active phase of and stable composting</u> was obtained on a single day
- The composting process produce low ammonia <u>emission (9.6 14.6 g/Nm³)</u>concentration
- •_The thermal-composter requires a small amount of energy-to produce high quality compos.

taround 1.44 kWh/kg-waste

- The produced compost can be a plant medium without passing the curing phase

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Declaration of interests

 \boxtimes The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

LAMPIRAN 3

1	An Innovative Thermal Composter to Accelerate Food Waste
2	Decomposition at the Household Level
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4	
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14	

15 ABSTRACT

An innovative, portable thermal composter was developed to accelerate the decomposition of 16 17 food waste at household. The study aimed to evaluate the performance of the composter by 18 assessing the quality of the compost produced. Food waste was chopped, mixed, stirred at 80 rpm, and heated to ~ 55 °C; thereafter, a bulking agent and stimulated microorganisms were 19 20 added to the mixture. The composter mixing speed was assessed to calculate the feasible 21 composting time. The results revealed that the active phase of composting process could be 22 completed in a day, producing good quality compost. The pH, electric conductivity, and C/N ratio of the compost was 6.72, 1,148–1,179 µScm⁻¹, and 20.38, respectively. The lowest 23 ammonia emissions (i.e., 7.2 g/Nm³) were produced on the sixth day. The total cost required 24 25 to process 1 kg of food waste in a day was only 2,097.76 Indonesian Rupiah (IDR), highlighting 26 the feasibility of this technology.

27 Keywords: food waste; active phase; rapid composter; thermal composter

28

29 1. INTRODUCTION

30 Nearly a third of the worldwide food production for human consumption is lost or 31 wasted, accounting for 1.3 billion tons of food per year. The high generation of food waste, representing a global economic loss, which is accounting around \$400 billion per yar (Raj et 32 33 al., 2022). Among various other types of waste, food waste may generate the highest 34 greenhouse gas (GHG) emissions, as it produces an enormous number of contaminants through 35 natural microbial degradation and other indirect processes, including transportation and the use of food processing machinery (Shen et al., 2020). Therefore, preventing food waste at the 36 37 household level, downstream of the food supply chain, is critical in limiting climate change (Parfitt et al., 2010). 38

39 There are several food waste management strategies, including composting (Cesaro et al., 2019), animal feed (Mo et al., 2018), anaerobic/aerobic digestion (Wainaina et al., 2020), 40 gasification, incineration (You et al., 2016), pyrolysis (Kim et al., 2020), and direct landfill 41 disposal (Goodman-Smith et al., 2020). Composting remains the most widespread solution in 42 43 developing countries, where it treats ~ 90–96% of food waste (Thi et al., 2015). Effective food 44 waste management has been proven to reduce pollutants, odors, and GHG emissions (Wei et 45 al., 2017; Zaman et al., 2021). In addition, composting is a common practice that can be easily implemented in residential households. 46

47 Composting systems at the household and community level have been discussed by Lu and Sidortsov (2019). Household-level composting equipment allows residents to compost 48 49 their food waste, ultimately reducing the volume of domestic waste transported to communal 50 waste processing facilities. There are, however, some challenges facing composting systems at 51 the household level. For example, there is the likelihood of odor emissions during the biodegradation process (Zhou et al., 2020). Moreover, the long processing times involved with 52 53 composting may lead to residents being unwilling to compost in their homes. The success of 54 household-level composting also depends on the knowledge, capacity, and self-awareness of 55 the residents who manage the household's waste (Fadhullah et al., 2022).

56 There are some techniques presented in previous literatures for reducing the processing 57 time of household composting. For instance, Kalamdhad et al. (2009) created a drum-shaped 58 thermophilic composter consisting of chambers with varying temperatures at its chamber. The thermophilic conditions allow for microbial metabolism activation, accelerating the 59 60 humification rate. The higher the temperature, the greater the microbiological activity will be 61 (Ottani et al., 2022). Food waste composting with the addition of microorganisms and thermal elements (0-100 °C) reached the maximum temperature faster (3 days), and the maturation 62 63 period decreased (4 weeks) (Charkhestani & Kebria, 2022). The composting time of 4 weeks 64 is still contrary to the community's wishes, where they want the composting process to happen 65 right after they throw the waste away in the composting machine. Awasthi et al. (2017) also found that adding multifunctional microorganisms produced better germination test results and 66 67 a composting period of 20 days. A recent study reveals that adding biochar can increase the 68 composting temperature and achieve an advanced thermophilic temperature in a short period 69 of time. Thus, making the composting time lasted for only 20 days (Jain et al., 2018). Oktiawan 70 et al. (2018) used a bulking agent at as much as 30% of the total waste to produce mature and 71 stable compost. A processed food waste size of ± 2 mm is ideal for microbes to carry out the 72 humification process and increase composting efficiency. Therefore, continuous aeration and rotation can also reduce the active phase of composting treatment from several weeks to only 73 74 4.5 days (Alkoaik, 2019). Since the processing time has become a limitation for applicability 75 at the household level, some modifications are still required to increase its efficiency and ensure 76 its feasibility as a household composter.

77 This study developed an innovative household composter with several modifications 78 which fill research gaps and addresses issues presented in previous studies. Furthermore, the 79 composter designed here is simple to use, portable, and operated automatically. Essentially, 80 food waste was stirred, heated, mixed, and decomposed in the composter, allowing active phase of composting to be obtained within a short period. The aim of the study was to demonstrate 81 82 the utility of a thermal composter prototype in different operational environments. 83 Furthermore, due to the limited research and the importance for further developing food waste 84 management strategies at the household level, the goal of this study was to demonstrate a 85 thermal composter that may accelerate the food waste composting process. The focus here was 86 on compost quality and morphology, ammonia (NH₃) gas emissions, and the total operating 87 cost.

89 2. METHODS

90 This research was conducted in the greenhouse of the Environmental Engineering Department, Faculty of Engineering, Diponegoro University. The thermal composter (see Fig. 91 92 1) was made of stainless steel (Type 316 austenitic, Indonesia) with dimensions of $60 \text{ cm} \times 30$ $cm \times 55$ cm (length \times width \times height). The composter frame was made of corrosion-resistant 93 94 galvalume, and its outer layer was made of white and green acrylic. The thermal composter 95 consisted of an inlet chamber, a food waste chopper, a spiral stirrer driven by a motor (0.5 hp, 3-phase, 1370 rpm, China), and a heater (12 V). The heater was set to ~ 80 °C to accelerate the 96 97 microbe metabolism and the humification rate. The bottom and sides of the composter were equipped with insulators to reduce heat loss. Finally, activated carbon and a UV lamp were 98 99 attached to the top of the composter to remove odors and microorganisms resulting from the 100 food waste decomposition (Zhou et al., 2020)



101

102 Fig. 1. Schematic diagram illustrating the design of the thermal composter developed in

103

this study.

105 Food waste was collected from a restaurant in Semarang City using trash bags and 106 transported to the Environmental Laboratory, Faculty of Engineering, Diponegoro University 107 for analysis. Prior to starting the experiment, the composition and physical properties of the 108 food waste were determined; thereafter, the food waste was mixed. The bulking agent used 109 here came from mature and stable compost with a size of 100 mesh. The food waste consisted 110 of various and mixed ingredients such as leftover rice, spinach, chayote, banana peels, 111 vegetable gravy, and many more. First, food waste (500 g per day) was added to the composter 112 inlet and chopped until the food waste particle size was homogenized to ~ 2 cm. Thereafter, 113 the bulking agent was added, accounting for as much as 30% (v/v) of the total food waste. The 114 mixture was then periodically stirred by the spiral stirrer and slowly pushed into the heating 115 chamber, where it was rotated for 1 min every 6 h. Despite the heater being set to 80 °C, the 116 mixture's temperature gradually decreased to 28-30 °C while in the cooling compartment or 117 outlet chamber. The composting cycle was carried out for 7 d by adjusting the rotational speed 118 of the spiral stirrer to 80 rpm. Compost was removed via the outlet chamber, with samples 119 collected daily and stored at 4 °C until further analysis.

120 Laboratory tests were conducted to ensure that the compost was actively produced. 121 Compost quality was assessed using the following parameters: (a) moisture content (MC), (b) 122 electric conductivity (EC), (c) pH, (d) temperature, (e) total nitrogen (TN), and (f) total organic 123 carbon (TOC). The gravimetric method was used to determine the MC, with the sample being 124 heated to 105 °C using an oven (Memmert UN 50, Germany). The Kjeldahl method was used 125 to determine TN, while TOC was assessed using the Walkley-Black method (UV-Vis 150 126 Spectrophotometer, Thermo Fisher Scientific, USA). The NH₃ emissions were assessed using the indophenol method and a spectrophotometer (Indonesia National Standard - SNI 19-127 128 7119.1-2005). The compost surface morphology was assessed using scanning electron microscopy (SEM) (Phenom ProX Desktop Scanning Electron Microscope, Thermo Fisher Scientific, USA) at a magnification of 100,000x. To do so, 2 g samples of three compost components (i.e., the bulking agent, food waste, and final compost) were collected and ovendried at 110 °C for 48 h (Memmert, Germany). The sample was ground, sieved through 200 mesh and fixed on a stub (circular metallic plate holder). Thereafter, the sample was sputter coated with gold (Sputter Coater, Quorum Q300T D Plus, UK), ensuring visibility of the morphology.

136 Plant growth tests were conducted to assess the quality of the compost as a plant growth 137 medium. This was done following the procedure described in Nguyen et al. (2020). Mung bean 138 (Vigna radiata) plants sourced from a farm shop (Semarang, Indonesia) were planted in nine 139 polybags of 5 cm \times 15 cm (width \times height) containing compost samples. All plants were treated 140 equally and received the same daily watering. At 7 d, the plants were removed from the 141 polybags, and several morphological parameters were measured, including height, weight, root 142 length, and the number of leaves. The plant heights were measured using a ruler, plant weights 143 were measured using an analytical balance (Mettler Toledo, Switzerland), and the germination 144 rates were observed daily. The presence of flies and odors was recorded following the 145 methodology described in Lleó et al. (2013). Finally, an economic evaluation was undertaken, aiming to assess the total costs incurred while operating the thermal composter. The total 146 147 electrical power required for each component of the composter was converted into Indonesian 148 Rupiah (IDR). Components that required electric power were the chopper, heater, spiral stirrer, 149 and UV lamp. Replacement costs of the activated carbon and bulking agent were also 150 calculated in detail. No labor or transportation costs were incurred.

151

152 3. RESULTS AND DISCUSSION

153 3.1. Moisture Content (MC)

154 The food waste contained an MC of 86.64% (Table 1); this was much higher than the 155 recommended MC (i.e., 40-60%) for favorable microbial growth (Guidoni et al., 2018). 156 However, food waste can produce a significant amount of gas and favors anaerobic processes, 157 which in turn can produce foul odors and contribute to the emission of GHGs (Onwosi et al., 2017). The bulking agent contained an MC of 43.16% (Table 1). Despite this, during the 158 159 composting process, the MC of the food waste and bulking agent mixture decreased drastically 160 to 32.58% after 24 h (Table 1); this was due to the chopping, heating, and stirring that took 161 place in the thermal composter. Water in the food waste evaporated during the heating and 162 thermophilic composting process; this resulted in the MC decreasing to 19.76% at 4 d, while at 5 and 7 d, MCs increased to 23.55% and 23.89%, respectively (Table 1). 163

The microbes almost became inactive after the MC dropped below 20%; at this stage, the compost products could have been bagged (Zhou et al., 2020). The bulking agent, owing to its compression resistance, helped maintain the porosity and structure of the mixture during composting. Indeed, no leachate was observed, indicating that the addition of the bulking agent influenced the total amount of leachate formed during composting (Guidoni et al., 2018). Finally, the stirring frequency helped maintain the porosity of the mixture and added oxygen to the system.

171

Table 1. Compost quality parameters and growth test results.

Parameter	Units	FW	BA	C-1	C-2	C-3	C-4	C-5	C-6	C-7
MC	%	86.64	43.16	32.58	25.00	25.50	19.76	23.55	24.07	23.89
pН	-	6.63	6.70	6.72	6.32	6.49	6.53	6.72	6.27	7.01
EC	µScm⁻¹	1,591	3,270	891	1,148	1,124	1,435	960	1,170	1,179
Growth test										
Height	cm	0	7.8	25.3	24.8	20.8	21.7	0	18.5	12.4
Weight	g	0	0.2403	0.4512	0.5116	0.4413	0.5308	0	0.5061	0.4843
Root length	cm	0	1.5	5.2	4.5	4.4	4.2	0	2.3	1
Leaf	single leaves	0	2	2	2	2	2	0	2	2

172 FW, food waste; BA, bulking agent; C-1–C-7, daily composting results (i.e., 7 d).

173

174 **3.2.** pH and Temperature

175 The food waste had an original pH of 6.63, while the bulking agent had a pH of 6.70 176 (Table 1). The daily addition of food waste did not significantly alter the mixture's pH, with the mixture at 1 and 7 d having pHs of 6.72 and 7.01, respectively. This pH range is ideal for 177 178 developing bacteria and fungi, thus, contributing to the composting process in producing high-179 quality and mature compost. Yuan & Zhu (2016) stated that the addition of a bulking agent 180 accelerates the increase in pH. Typically, food waste that undergoes natural decomposition 181 produces an acidic pH due to the formation of organic acid (Guidoni et al., 2018). The pH then 182 begins to increase due to the ammonification of organic matter, where organic nitrogen is 183 transformed into amide and ammoniacal nitrogen. The formation of NH₃, an alkaline reaction, 184 also increases the pH. Zhou et al. (2020) found that processing food waste using a composter 185 produced weakly acidic pHs during the initial and cooling stages, while an increase in pH was 186 observed during the heating and thermophilic stages. Ultimately, the changes in pH may be 187 attributable to pH imbalances caused by the microbial metabolic activity. Based on the pH value results, compost produced by the thermal composter could be taken during any of the 188 189 seven composting process days and be used for agricultural purposes.



191

Fig. 2. Graph illustrating the temperature of the thermal composter heater (dashed line),

line).

as well as the compost temperature in the heating (solid line) and outlet chambers (dotted

- 193
- 194

The heater of the thermal composter was set to 80 °C, ensuring consistent thermophilic 195 196 conditions in the heating chamber (Fig. 2). The composting temperature in the heating chamber rose rapidly from 26.3 °C to 52.63 °C within the first 20 min (Fig. 2). Within the same period, 197 198 however, the composting temperature in the outlet chamber only rose from 26.3 °C to 37.44 199 °C (Fig. 2). A temperature of 52.63 °C in the heating chamber was beneficial for thermophilic 200 microbial metabolism. At 7 d, the compost temperatures in the heating and outlet chambers 201 were 53.69 °C and 40.69 °C, respectively (Fig. 2), indicating rapid food waste composting in 202 the thermal composter. The thermophilic temperature positively impacts the decomposition 203 rate of food waste so that the composting process can be completed in a day. In addition, this 204 thermophilic temperature decreases food waste's water content, where the initial 86.64% food 205 wastewater content decreases to 32.58% (day 1) and 23.89% (day 7).

- 206
- 207 **3.3.** Electric Conductivity (EC)

The original food waste and bulking agent EC values were 1,591 μ Scm⁻¹ and 3,270 μ Scm⁻¹, respectively. The mixture had an EC value of 0.891 μ Scm⁻¹ after being processed for 1 d in the thermal composter. The observed EC value decrease was due to the chopping, heating, and thermophilic decomposition that occurred in the thermal composter. However, the overall EC value during the composting process did not alter significantly and had a range of 1,148–1,179 μ Scm⁻¹. EC values reflect the salinity of the composting matrix (Onwosi et al., 2017). Furthermore, compost is safe for planting when it displays an EC value < 4,000 μ Scm⁻¹ ¹. In this study, EC values were consistently < 2,000 µScm⁻¹ during the composting process,
and thus, had no impact on biological activity (Mujtaba et al., 2021).

217

218 3.4. Flies and Odor

219 Flies typically land on food waste soon after its disposal. However, in this study, no 220 flies were observed for 7 d, implying that the food waste and the products of its decomposition did not attract flies. Stirring of the mixture every 6 h did not affect the number of flies. A 221 previous study found that the capacity of the composter was sufficient to stabilize the organic 222 223 waste (Blazy et al., 2014). Guidoni et al. (2018) found that flies disappeared after the eleventh day of composting three treatments which varied in their ratio of rice husk to raw fruit and 224 225 vegetables (i.e., 70:30, 50:50, 30:70; v:v). No strong odor was detected during this study. The 226 bulking agent addition allowed the diffusion of gases and it maintained an aerobic composting process. In addition, bulking agents enhanced the inter-particle voids in the composite pile, 227 228 thereby increasing the air permeability and regulating the humidity of the compost substrate 229 (Yang et al., 2019).



Fig. 3. Graph illustrating ammonia (NH₃) concentrations in ambient air (squares) and NH₃
 emissions during seven days of composting using a thermal composter (circles).

233

234 3.5. NH₃ Emissions

Emission of NH₃ varies according to the substrate composition, particle sizes, moisture, 235 236 oxygen distribution, initial temperature gradients, and the overall process conditions (Onwosi et al., 2017). The first day of the composting process produced an NH₃ emission of 4.1 g/Nm³, 237 with an increase to 9.6 g/Nm³ occurring at 2 d (Fig. 3). This increase was likely due to the 238 239 addition of food waste; moreover, the increasing trend continued until 7 d, which saw an NH₃ emission of 21.2 g/Nm³ (Fig. 3). The NH₃ concentrations in ambient air ranged from 1.6–5.4 240 241 g/Nm³, with the lowest concentration (i.e., 1.6 g/Nm³) occurring at 4 d and the highest 242 concentration (i.e., 5.4 g/Nm³) at 6 d (Fig. 3). Overall, the NH₃ concentrations in ambient air did not change significantly (p > 0.05). 243

244

245 **3.6.** Total Organic Carbon (TOC)

246 Higher levels of TOC degradation indicate more stable compost (Sharma et al., 2017). 247 After 1 d in the thermal composter, the TOC of the compost mixture decreased drastically by 75.94%. The TOC for the remaining days ranged from 77.42–79.94%, lower than the initial 248 249 TOC level (See Fig. 4). The decrease observed here supports Lalremruati & Devi (2021), who 250 stated that the decomposition of vegetable waste is straightforward, owing to it mostly 251 containing cellulose. Liu et al. (2018) reported a decrease in vegetable waste TOC ranging from 11.4-32.1%, when using sawdust, cow dung, and inoculum for 40 d. Notably, the TOC 252 253 decrease observed in this study remained stable (i.e., 77.42–79.94%) throughout the 7-d period, despite the addition of 500 g of food waste per day (Fig. 4). Indeed, these results indicate that 254

the thermal composter is effective in accelerating the degradation of TOC, owing to theintegration of the mixing system, heating parameters, and bulking agent.



Fig. 4. Graph illustrating the level of total organic carbon (TOC) in food waste during seven
 days of composting using a thermal composter.

260

257

261 **3.7.** Total Nitrogen (TN)

262 The initial TN value decreased significantly at 2 and 3 d of the composting process. The 263 decrease in TN is caused by the evaporation of ammonia, and lower pH results in less organic 264 matter mineralization (Wang et al., 2017). As it may see in Fig. 3, the ammonia emission 265 increased from 9.6 to 14.6 g/Nm³. Therefore, the pH values for 2 and 3 d remain at 6.32 and 266 6.49, respectively, which are lesser than the pH at 1, 4, 5, and 7 d. Indeed, several studies have 267 attributed the decrease in TN to the volatilization of NH₃, when temperature and pH were more than 45 °C (Cáceres et al., 2018; Zhou et al., 2018). Nguyen et al. (2020) found that TN was 268 269 influenced by temperature; in addition, the optimal TN was found in experiments that were rotated once per day and exhibited a C/N ratio of 20. Regarding the production of compost 270 from domestic organic waste (Indonesia National Standard - SNI 19-7030-2004), the optimal 271 TN for compost is a minimum of 0.40%. Indeed, the results obtained here confirm that the TN 272

content in the compost collected at 1, 4, 6, and 7 d meet this quality standard. The highest TN
content (i.e., 0.49%) was found on the first day, while the lowest TN content (i.e., 0.28%),
which does not meet the quality standard, was found at 3 d. Ultimately, temperature and the
composition of the compost raw material can affect the TN in the compost.

277

278 3.8. C/N Ratio

279 The C/N ratio is a conventional parameter used to assess the composting process (Zhou 280 et al., 2018). The reduction of the C/N ratio due to the simultaneous consumption of carbon 281 and nitrogen organic substrates indicates an effective composting process (Wang et al., 2016), 282 with composts that display a C/N ratio < 20 being considered mature. According to the Ministry 283 of Agriculture of Indonesia Number: 28/Permentan/SR.30/5/2009, organic and biological 284 fertilizers, as well as soil enhancers, typically exhibit C/N ratios within the range of 15–25. The 285 composting process in this study was 500 g of food waste being used as the initial compost raw 286 material; on each of the ensuing days, an additional 500 g of food waste with a typical 287 composition was added. The results reveal that the food waste at 2, 3, and 5 d had C/N ratios > 288 25, ultimately displaying poor composting conditions; whereas at 1, 4, 6, and 7 d, the C/N ratios 289 ranged from 20–25, indicating good compositions. The C/N ratio variation found in this study was ultimately driven by differences in the daily food waste composition and quantity. 290

291

292 **3.9.** SEM Images

SEM was used as an additional technique to assess micro-changes in the surface morphology of different compost components (See Fig. 5). In SEM, a focused high-energy electron beam is used to scan the surface of a specimen (Oñiguez et al., 2011). The resulting high-quality images provide information about the sample's external morphology (texture) and crystalline structure. Micrographs of food waste samples, compost, and the bulking agent (as

298 provided in supplementary materials) reveal different particle sizes and distributions per unit 299 area, as well as heterogeneity in particle compaction. Moreover, micrographs showed that the 300 compost sample exhibited larger pore diameters and had no particle compaction. However, 301 while the initial food waste displayed small pore diameters, particle compaction was present. 302 Biodegradation has been shown to lead to improved texture and particle compaction (Arora & 303 Kaur, 2019). The same result was shown by Ajmal et al. (2021), where the food waste has 304 tightened microscopic structure compared to the compost product. This result may be due to 305 the microorganism activity, which reduces the particle size and increase the holes of the 306 fermented food waste. Moreover, the surface roughness and irregular pore shapes shown in the 307 compost product may indicate the possibility of microbial degradation during the composting 308 process (Ma et al., 2022).



(a)

(b)

(c)

309 Fig. 5. Surface morphology of (a) bulking agent, (b) food waste, and (c) compost produced
310 from thermal composter at 10,000x magnification. The red arrows indicate the distribution of
311 particle sizes and the circles indicate the pore diameters.

312

313 **3.10.** Growth test

Compost products derived from food waste generally provide improved plant growthconditions. The plant growth tests revealed rapid and consistent daily mung bean growth.

Growth tests using compost taken from six of the seven composting days (i.e., 1–4, 6, and 7 d) as well as the bulking agent alone, resulted in increased plant height and weight (Table 1). Growth tests using the fresh food waste alone, however, did not facilitate any plant growth (Table 1), with the waste beginning to rot at 1 d. Moreover, no plant growth was observed t 5 d (Table 1); this was due to the accumulation of acidic decomposition products. Ultimately, the results presented here agree with the literature that compost from food waste can be used as a plant growth medium (Nguyen et al., 2020).

323

324 3.11. Practical Evaluation and Future Research Direction

325 Household food waste composting does not require labor, transport, sorting, or 326 processing fees. Zhou et al. (2020) believe that the in-situ composting system differs from the 327 centralized composting system. The thermal composter used in this study processed 1 kg of 328 food waste per day, using a total electrical power of 1.452 kWh. This total power consists of 329 the shredding unit (i.e., 0.00375 kWh), the spiral stirring unit (i.e., 0.00828 kWh), and the 330 heating unit (i.e., 1.440 kWh). To process 1 kg of food waste in a day, the heating unit required 331 the most power as it operated for 24 h, while the shredding and stirring units operated for only 332 30 and 80 s, respectively. The total cost for operating the thermal composter amounted to 333 2,097.76 IDR to process 1 kg of food waste in a single day. The total cost of the composter 334 developed by Zhou et al. (2020) requires \$0.033 (445.98 IDR) per kg for food waste, but the 335 composting time is longer (four days). Even though the electricity cost is 2,097.76 IDR to 336 process 1 kg of food waste in a day, food waste composting using a thermal composter still get 337 profits from selling the compost product as a fertilizer for 5,000.00 IDR (Paduloh & Rosihan, 338 2021). Moreover, the compost improves soil quality, assists the remediation of contaminated 339 soil and reduces the need for chemical fertilizers. Solar cells can be an alternative AC power

source for thermal composter operations. In addition, it is necessary to increase publicacceptance of the thermal composter so that they can use it to treat food waste.

342

343 4. CONCLUSION

Thermal composting is considered a straightforward and effective strategy to manage 344 345 household food waste. In this study, an innovative household thermal composter was developed 346 and its feasibility assessed. Active phase of composting was finished after a single day of treatment, with MC, pH, temperature, EC, TOC, TN, C/N ratios, and SEM images meeting the 347 348 criteria required for high quality compost. Regardless, the compost obtained after a single day was used successfully as a plant growth medium, confirming the compost's low toxicity level. 349 350 Furthermore, the composter was shown to require a small amount of daily electricity to process 351 food waste.

352

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358

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360 Badrus Zaman: Conceptualization, Supervision, Writing-Review & Editing Nurandani

361 Hadiyanti: Validation, Resources Software Purwono: Investigation, Formal Analysis, Project

362 Administration Bimastyaji Surya Ramadan: Writing-Review & Editing, Data Curation

363

364 CONFLICT OF INTEREST

- 365 The authors declare that there is no conflict of interest exists.
- 366

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1	An Innovative Thermal Composter to Accelerate Food Waste					
2	Decomposition at the Household Level					
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15 ABSTRACT

An innovative, portable thermal composter was developed to accelerate the decomposition of 16 17 food waste at household. The study also-aimed to evaluate the performance of the composter 18 by assessing the quality of the compost produced. Food waste was chopped, mixed, stirred at 80 rpm, and heated to ~ 55 °C; thereafter, a bulking agent and stimulated microorganisms were 19 20 added to the mixture. The composter mixing speed was assessed to calculate the feasible 21 composting time. The results revealed that the active phase of composting process could be 22 completed in a_single day, producing high quality, mature good quality compost. The pH, 23 electric conductivity, and C/N ratio of the compost was 6.72, 1,148–1,179 µScm⁻¹, and 20.38, 24 respectively. The lowest ammonia emissions (i.e., 7.2 g/Nm³) were produced on the sixth day. 25 The total cost required to process 1 kg of food waste in a day was only 2,097.76 Indonesian 26 Rupiah (IDR), highlighting the feasibility of this technology.

27 Keywords: food waste; mature active phase compost; rapid composter; thermal composter

28

29 1. INTRODUCTION

30 Nearly a third of the worldwide food production for human consumption is lost or 31 wasted, accounting for 1.3 billion tons of food per year. The high generation of food waste, representing a global economic loss, which is accounting around \$400 billion per yar -(Raj et 32 33 al., 2022Schanes et al., 2018). Among various other types of waste, food waste may generate 34 the highest greenhouse gas (GHG) emissions, as it produces an enormous number of 35 contaminants through natural microbial degradation and other indirect processes, including 36 transportation and the use of food processing machinery (Shen et al., 2020). Therefore, 37 preventing food waste at the household level, downstream of the food supply chain, is critical in limiting climate change (Parfitt et al., 2010). 38

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39 -There are several food waste management strategies, including composting (Cesaro et al., 2019), animal feed (Mo et al., 2018), anaerobic/aerobic digestion (Wainaina et 40 41 al., 2020), gasification, incineration (You et al., 2016), pyrolysis (Kim et al., 2020), and direct 42 landfill disposal (Goodman-Smith et al., 2020). Composting remains the most widespread 43 solution in developing countries, where it treats ~ 90-96% of food waste (Thi et al., 2015). 44 Effective food waste management has been proven to reduce pollutants, odors, and GHG 45 emissions (Wei et al., 2017; Zaman et al., 2021). Awasthi et al. (2017) also found that adding 46 multifunctional microorganisms produced better germination test results and a composting 47 period of 20 d. Nevertheless. In addition, composting is a common practice that can be easily 48 implemented in residential households.

49 Composting systems at the household and community level have been discussed by Lu and Sidortsov (2019). Household-level composting equipment allows residents to compost 50 51 their food waste, ultimately reducing the volume of domestic waste transported to communal 52 waste processing facilities. There are, however, some challenges facing composting systems at 53 the household level. For example, there is the likelihood of odor emissions during the 54 biodegradation process (Zhou et al., 2020). Moreover, the long processing times involved with 55 composting may lead to residents being unwilling to compost in their homes. The success of 56 household-level composting also depends on the knowledge, capacity, and self-awareness of 57 the residents who manage the household's waste (Fadhullah et al., 2022).

Several studies have discussed how to accelerate the composting process, as well as
reduce the odors and GHGs emitted during the process. For instance, Kalamdhad et al. (2009)
ereated a drum shaped thermophilic composter consisting of chambers with varying
temperatures, namely the inlet (60–70 °C), processing (50–60 °C), and outlet chamber (30–38
°C). The thermophilic conditions allow for microbial metabolism activation, accelerating the
humification rate. Composters are also able to exhibit an aeration process which reduces the

64	odors and GHGs emitted by the anaerobic decomposition (Zaman et al., 2021). Margaritis et
65	al. (2018) found that compost physical properties increased as a result of an increase in the
66	porosity of different bulking agents, which in turn allowed for better aeration. Oktiawan et al.
67	(2018) used a bulking agent at as much as 30% of the total waste to produce mature and stable
68	compost. A processed food waste size of \pm 2 mm is ideal for microbes to carry out the
69	humification process and increase composting efficiency-Awasthi et al. (2017) also found that
70	adding multifunctional microorganisms produced better germination test results and a
71	composting period of 20 d. Nevertheless, Blazy et al. (2014) suggests that olfactory
72	measurements should be correlated with gaseous emissions to allow for a more accurate
73	evaluation of odor emissions during food waste composting. Thermal composters are known
74	for having a faster composting process; however, some modifications are required to increase
75	its efficiency and ensure its feasibility as a household composter. There are some techniques
76	presented in previous literatures for reducing the processing time of household composting.
77	For instance, Kalamdhad et al. (2009) created a drum-shaped thermophilic composter
78	consisting of chambers with varying temperatures at its chamber, namely the inlet (60-70 °C),
79	processing (50-60 °C), and outlet chamber (30-38 °C). The thermophilic conditions allow for
80	microbial metabolism activation, accelerating the humification rate. The higher the
81	temperature, the greater the microbiological activity will be (Ottani et al., 2022). Food waste
82	composting with the addition of microorganisms and thermal elements (0-100 °C) reached the
83	maximum temperature faster (3 days), and the maturation period decreased (4 weeks)
84	(Charkhestani & Kebria, 2022). The composting time of 4 weeks is still contrary to the
85	community's wishes, where they want the composting process to happen right after they throw
86	the waste away in the composting machine. Awasthi et al. (2017) also found that adding
87	multifunctional microorganisms produced better germination test results and a composting
88	period of 20 days. A recent study reveals that adding biochar can increase the composting
l	

89	temperature and achieve an advanced thermophilic temperature in a short period of time. Thus,
90	making the composting time lasted for only 20 days (Jain et al., 2018). Oktiawan et al. (2018)
91	used a bulking agent at as much as 30% of the total waste to produce mature and stable compost.
92	<u>A processed food waste size of ± 2 mm is ideal for microbes to carry out the humification</u>
93	process and increase composting efficiency. Therefore, continuous aeration and rotation can
94	also reduce the active phase of composting treatment from several weeks to only 4.5 days
95	(Alkoaik, 2019). Since the processing time has become a limitation for applicability at the
96	household level, sThermal composters are known for having a faster composting process;
97	however, some modifications are still required to increase its efficiency and ensure its
98	feasibility as a household composter.

99 This study developed an innovative household composter with several modifications 100 which fill research gaps and addresses issues presented in previous studies. Furthermore, the 101 composter designed here is simple to use, portable, and operated using a 102 smartphoneautomatically. Essentially, food waste was stirred, heated, mixed, and decomposed 103 in the composter, allowing mature and stable active phase of composting to be produced 104 obtained within a short period. The aim of the study was to demonstrate the utility of a thermal 105 composter prototype in different operational environments. Furthermore, due to the limited 106 research and the importance for further developing food waste management strategies at the 107 household level, the goal of this study was to demonstrate a thermal composter that may 108 accelerate the food waste composting process. The focus here was on compost quality and 109 morphology, ammonia (NH₃) gas emissions, and the total operating cost.

110

111 **2. METHODS**

112 113 This research was conducted in the greenhouse of the Environmental Engineering* Formatted: Tab stops: 3.64", Left

Department, Faculty of Engineering, Diponegoro University. The thermal composter (see Fig.

114 1) was made of stainless steel (Type 316 austenitic, Indonesia) with dimensions of $60 \text{ cm} \times 30$ 115 cm \times 55 cm (length \times width \times height). The composter frame was made of corrosion-resistant 116 galvalume, and its outer layer was made of white and green acrylic. The thermal composter 117 consisted of an inlet chamber, a food waste chopper, a spiral stirrer driven by a motor (0.5 hp, 3-phase, 1370 rpm, China), and a heater (12 V). The heater was set to ~ 80 °C to accelerate the 118 119 microbe metabolism and the humification rate-(Zhou et al., 2020). The bottom and sides of the 120 composter were equipped with insulators to reduce heat loss. Finally, activated carbon and a 121 UV lamp were attached to the top of the composter to remove odors and microorganisms 122 resulting from the food waste decomposition (Zhou et al., 2020)



Food waste was collected from a restaurant in Semarang City using trash bags andtransported to the Environmental Laboratory, Faculty of Engineering, Diponegoro University

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129 for analysis. Prior to starting the experiment, the composition and physical properties of the 130 food waste were determined; thereafter, the food waste was mixed. The bulking agent used 131 here came from mature and stable compost with a size of 100 mesh. The food waste consisted 132 of various and mixed ingredients such as leftover rice, spinach, chayote, and banana peels, 133 vegetable gravy, and many more. First, food waste (500 g per day) was added to the composter 134 inlet and chopped until the food waste particle size was homogenized to ~ 2 cm. Thereafter, 135 the bulking agent was added, accounting for as much as 30% (v/v) of the total food waste. The 136 mixture was then periodically stirred by the spiral stirrer and slowly pushed into the heating 137 chamber, where it was rotated for 1 min every 6 h. Despite the heater being set to 80 °C, the 138 mixture's temperature gradually decreased to 28-30 °C while in the cooling compartment or outlet chamber. The composting cycle was carried out for 7 d by adjusting the rotational speed 139 140 of the spiral stirrer to 80 rpm. Mature eCompost was removed via the outlet chamber, with 141 samples collected daily and stored at 4 °C until further analysis.

142 Laboratory tests were conducted to ensure that the compost was mature and 143 stableactively produced. Compost quality was assessed using the following parameters: (a) 144 moisture content (MC), (b) electric conductivity (EC), (c) pH, (d) temperature, (e) total 145 nitrogen (TN), and (f) total organic carbon (TOC). The gravimetric method was used to 146 determine the MC, with the sample being heated to 105 °C using an oven (Memmert UN 50, Germany). The Kjeldahl method was used to determine TN, while TOC was assessed using the 147 148 Walkley-Black method (UV-Vis 150 Spectrophotometer, Thermo Fisher Scientific, USA). The 149 NH₃ emissions were assessed using the indophenol method and a spectrophotometer (Indonesia 150 National Standard - SNI 19-7119.1-2005). The compost surface morphology was assessed 151 using scanning electron microscopy (SEM) (Phenom ProX Desktop Scanning Electron Microscope, Thermo Fisher Scientific, USA) at a magnification of 100,000x. To do so, 2 g 152 samples of three compost components (i.e., the bulking agent, food waste, and final compost) 153

were collected and oven-dried at 110 °C for 48 h (Memmert, Germany). The sample was
ground, sieved through 200 mesh and fixed on a stub (circular metallic plate holder).
Thereafter, the sample was sputter coated with gold (Sputter Coater, Quorum Q300T D Plus,
UK), ensuring visibility of the morphology.

158 Plant growth tests were conducted to assess the quality of the compost as a plant growth 159 medium; this This was done following the procedure described in Nguyen et al. (2020). Mung 160 bean (Vigna radiata) plants sourced from a farm shop (Semarang, Indonesia) were planted in 161 nine polybags of 5 cm \times 15 cm (width \times height) containing compost samples. All plants were 162 treated equally and received the same daily watering. At 7 d, the plants were removed from the 163 polybags, and several morphological parameters were measured, including height, weight, root length, and the number of leaves. The plant heights were measured using a ruler, plant weights 164 165 were measured using an analytical balance (Mettler Toledo, Switzerland), and the germination rates were observed daily. The presence of flies and odors was recorded following the 166 167 methodology described in Lleó et al. (2013). Finally, an economic evaluation was undertaken, 168 aiming to assess the total costs incurred while operating the thermal composter. The total 169 electrical power required for each component of the composter was converted into Indonesian 170 Rupiah (IDR). Components that required electric power were the chopper, heater, spiral stirrer, 171 and UV lamp. Replacement costs of the activated carbon and bulking agent were also 172 calculated in detail. No labor or transportation costs were incurred.

173

174 3. RESULTS AND DISCUSSION

175 3.1. Moisture Content (MC)

The food waste contained an MC of 86.64% (Table 1); this was much higher than the
recommended MC (i.e., 40–60%) for favorable microbial growth (Guidoni et al., 2018).
However, food waste can produce a significant amount of gas and favors anaerobic processes,

179	which in turn can produce foul odors and contribute to the emission of GHGs (Onwosi et al.,
180	2017). The bulking agent contained an MC of 43.16% (Table 1). Despite this, during the
181	composting process, the MC of the food waste and bulking agent mixture decreased drastically
182	to 32.58% after 24 h (Table 1); this was due to the chopping, heating, and stirring that took
183	place in the thermal composter. Water in the food waste evaporated during the heating and
184	thermophilic composting process; this resulted in the MC decreasing to 19.76% at 4 d, while
185	at 5 and 7 d, MCs increased to 23.55% and 23.89%, respectively (Table 1).

The microbes almost became inactive after the MC dropped below 20%; at this stage, the compost products could have been bagged (Zhou et al., 2020). The bulking agent, owing to its compression resistance, helped maintain the porosity and structure of the mixture during composting. Indeed, no leachate was observed, indicating that the addition of the bulking agent influenced the total amount of leachate formed during composting (Guidoni et al., 2018). Finally, the stirring frequency helped maintain the porosity of the mixture and added oxygen to the system.

193

Table 1. Compost quality parameters and growth test results.

Parameter	Units	FW	BA	C-1	C-2	C-3	C-4	C-5	C-6	C-7
MC	%	86.64	43.16	32.58	25.00	25.50	19.76	23.55	24.07	23.89
pН	-	6.63	6.70	6.72	6.32	6.49	6.53	6.72	6.27	7.01
EC	µScm ⁻¹	1,591	3,270	0, 891	1,148	1,124	1,435	960	1,170	1,179
Growth test										
Height	cm	0	7 <u>.</u> 8	25.3	24.8	20.8	21.7	0	18.5	12.4
Weight	g	0	0.2403	0.4512	0.5116	0.4413	0.5308	0	0.5061	0.4843
Root length	cm	0	1.5	5.2	4.5	4.4	4.2	0	2.3	1
Leaf	single leaves	0	2	2	2	2	2	0	2	2

194 FW, food waste; BA, bulking agent; C-1–C-7, daily composting results (i.e., 7 d).

195

196 3.2. pH and Temperature

197 The food waste had an original pH of 6.63, while the bulking agent had a pH of 6.70 198 (Table 1). The daily addition of food waste did not significantly alter the mixture's pH, with 199 the mixture at 1 and 7 d having pHs of 6.72 and 7.01, respectively. <u>This pH range is ideal for</u>

200 developing bacteria and fungi, thus, contributing to the composting process in producing high-201 quality and mature compost. -Yuan & Zhu (2016) stated that the addition of a bulking agent 202 accelerates the increase in pH. Typically, food waste that undergoes natural decomposition 203 produces an acidic pH due to the formation of organic acid (Guidoni et al., 2018). The pH then begins to increase due to the ammonification of organic matter, where organic nitrogen is 204 205 transformed into amide and ammoniacal nitrogen. The formation of NH₃, an alkaline reaction, 206 also increases the pH. Zhou et al. (2020) found that processing food waste using a composter 207 produced weakly acidic pHs during the initial and cooling stages, while an increase in pH was 208 observed during the heating and thermophilic stages. Ultimately, the changes in pH may be 209 attributable to pH imbalances caused by the microbial metabolic activity. Based on the pH 210 value results, compost produced by the thermal composter could be taken during any of the 211 seven composting process days and be used for agricultural purposes.



212

213 Fig. 2. Graph illustrating the temperature of the thermal composter heater (dashed line),



215

line).

216

217	The heater of the thermal composter was set to 80 $^\circ$ C, ensuring consistent thermophilic
218	conditions in the heating chamber (Fig. 2). The composting temperature in the heating chamber
219	rose rapidly from 26.3 °C to 52.63 °C within the first 20 min (Fig. 2). Within the same period,
220	however, the composting temperature in the outlet chamber only rose from 26.3 $^\circ C$ to 37.44
221	$^{\circ}\text{C}$ (Fig. 2). A temperature of 52.63 $^{\circ}\text{C}$ in the heating chamber was beneficial for thermophilic
222	microbial metabolism. At 7 d, the compost temperatures in the heating and outlet chambers
223	were 53.69 $^{\rm o}{\rm C}$ and 40.69 $^{\rm o}{\rm C},$ respectively (Fig. 2), indicating rapid food waste composting in
224	the thermal composter. The thermophilic temperature positively impacts the decomposition
225	rate of food waste so that the composting process can be completed in a day. In addition, this
226	thermophilic temperature decreases food waste's water content, where the initial 86.64% food
227	wastewater content decreases to 32.58% (day 1) and 23.89% (day 7).

228

229 3.3. Electric Conductivity (EC)

230 The original food waste and bulking agent EC values were 1,591 µScm⁻¹ and 3,270 231 µScm⁻¹, respectively. The mixture had an EC value of 0.891 µScm⁻¹ after being processed for 1 d in the thermal composter. The observed EC value decrease was due to the chopping, 232 233 heating, and thermophilic decomposition that occurred in the thermal composter. However, the overall EC value during the composting process did not alter significantly and had a range of 234 235 1,148–1,179 µScm⁻¹. EC values reflect the salinity of the composting matrix (Onwosi et al., 2017). Furthermore, compost is safe for planting when it displays an EC value < $4,000 \ \mu Scm^{-1}$ 236 237 ¹. In this study, EC values were consistently $< 2,000 \ \mu \text{Scm}^{-1}$ during the composting process, 238 and thus, had no impact on biological activity (Mujtaba et al., 2021).

239

240 3.4. Flies and Odor

241 Flies typically land on food waste soon after its disposal. However, in this study, no 242 flies were observed for 7 d, implying that the food waste and the products of its decomposition 243 did not attract flies. Stirring of the mixture every 6 h did not affect the number of flies. A 244 previous study found that the capacity of the composter was sufficient to stabilize the organic waste (Blazy et al., 2014). Guidoni et al. (2018) found that flies disappeared after the eleventh 245 246 day of composting three treatments which varied in their ratio of rice husk to raw fruit and 247 vegetables (i.e., 70:30, 50:50, 30:70; v:v). No strong odor was detected during this study. The 248 bulking agent addition allowed the diffusion of gases and it maintained an aerobic composting 249 process. In addition, bulking agents enhanced the inter-particle voids in the composite pile, thereby increasing the air permeability and regulating the humidity of the compost substrate 250 251 (Yang et al., 2019).



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Fig. 3. Graph illustrating ammonia (NH₃) concentrations in ambient air (squares) and NH₃
 emissions during seven days of composting using a thermal composter (circles).

255

256 3.5. NH₃ Emissions

257 Emission of NH₃ varies according to the substrate composition, particle sizes, moisture, 258 oxygen distribution, initial temperature gradients, and the overall process conditions (Onwosi 259 et al., 2017). The first day of the composting process produced an NH₃ emission of 4.1 g/Nm³, with an increase to 9.6 g/Nm³ occurring at 2 d (Fig. 3). This increase was likely due to the 260 261 addition of food waste; moreover, the increasing trend continued until 7 d, which saw an NH₃ 262 emission of 21.2 g/Nm3 (Fig. 3). The NH3 concentrations in ambient air ranged from 1.6-5.4 263 g/Nm³, with the lowest concentration (i.e., 1.6 g/Nm³) occurring at 4 d and the highest 264 concentration (i.e., 5.4 g/Nm³) at 6 d (Fig. 3). Overall, the NH₃ concentrations in ambient air 265 did not change significantly (p > 0.05).

266

267 3.6. Total Organic Carbon (TOC)

268 Higher levels of TOC degradation indicate more stable compost (Sharma et al., 2017). After 1 d in the thermal composter, the TOC of the compost mixture decreased drastically by 269 270 75.94% (Fig. 4). The TOC for the remaining days ranged from 77.42–79.94%, lower than the 271 initial TOC level (See Fig. 4). The decrease observed here supports Lalremruati & Devi (2021), 272 who stated that the decomposition of vegetable waste is straightforward, owing to it mostly 273 containing cellulose. Liu et al. (2018) reported a decrease in vegetable waste TOC ranging from 274 11.4-32.1%, when using sawdust, cow dung, and inoculum for 40 d. Notably, the TOC 275 decrease observed in this study remained stable (i.e., 77.42-79.94%) throughout the 7-d period, 276 despite the addition of 500 g of food waste per day (Fig. 4). Indeed, these results indicate that the thermal composter is effective in accelerating the degradation of TOC, owing to the 277 278 integration of the mixing system, heating parameters, and bulking agent.



d meet this quality standard. The highest TN content (i.e., 0.49%) was found on the first day,
while the lowest TN content (i.e., 0.28%), which does not meet the quality standard, was found
at 3 d. Ultimately, temperature and the composition of the compost raw material can affect the
TN in the compost.

301

302 3.8. C/N Ratio

303 The C/N ratio is a conventional parameter used to assess the composting process (Zhou 304 et al., 2018). The reduction of the C/N ratio due to the simultaneous consumption of carbon 305 and nitrogen organic substrates indicates an effective composting process (Wang et al., 2016), 306 with composts that display a C/N ratio < 20 being considered mature. According to the Ministry 307 of Agriculture of Indonesia Number: 28/Permentan/SR.30/5/2009, organic and biological 308 fertilizers, as well as soil enhancers, typically exhibit C/N ratios within the range of 15-25. The 309 composting process in this study was 500 g of food waste being used as the initial compost raw 310 material; on each of the ensuing days, an additional 500 g of food waste with a different typical 311 composition was added. The results reveal that the food waste at 2, 3, and 5 d had C/N ratios > 312 25, ultimately displaying poor composting conditions; whereas at 1, 4, 6, and 7 d, the C/N ratios 313 ranged from 20-25, indicating good compositions. The C/N ratio variation found in this study 314 was ultimately driven by differences in the daily food waste composition and quantity.

315

316 3.9. SEM Images

SEM was used as an additional technique to assess micro-changes in the surface morphology of different compost components <u>(See Fig. 5)</u>. In SEM, a focused high-energy electron beam is used to scan the surface of a specimen (Oñiguez et al., 2011). The resulting high-quality images provide information about the sample's external morphology (texture) and crystalline structure. Micrographs of food waste samples, compost, and the bulking agent (as

322	provided in supplementary materials) reveal different particle sizes and distributions per unit
323	area, as well as heterogeneity in particle compaction. Moreover, micrographs showed that the
324	compost sample exhibited larger pore diameters and had no particle compaction. However,
325	while the initial food waste displayed small pore diameters, particle compaction was present.
326	Biodegradation has been shown to lead to improved texture and particle compaction (Arora &
327	Kaur, 2019). The same result was shown by Ajmal et al. (2021), where the food waste has
328	tightened microscopic structure compared to the compost product. This result may be due to
329	the microorganism activity, which reduces the particle size and increase the holes of the
330	fermented food waste. Moreover, the surface roughness and irregular pore shapes shown in the
331	compost product may indicate the possibility of microbial degradation during the composting
332	process (Ma et al., 2022).



<u>(a)</u>



333	Fig. 5. Surface morphology of (a) bulking agent, (b) food waste, and (c) compost produced
334	from thermal composter at 10,000x magnification. The red arrows indicate the distribution of
335	particle sizes and the circles indicate the pore diameters.
336	
337	

338 **3.10.** Growth test

339 Compost products derived from food waste generally provide improved plant growth 340 conditions. The plant growth tests revealed rapid and consistent daily mung bean growth. 341 Growth tests using compost taken from six of the seven composting days (i.e., 1-4, 6, and 7 d) as well as the bulking agent alone, resulted in increased plant height and weight (Table 1). 342 343 Growth tests using the fresh food waste alone, however, did not facilitate any plant growth 344 (Table 1), with the waste beginning to rot at 1 d. Moreover, no plant growth was observed t 5 345 d (Table 1); this was due to the accumulation of acidic decomposition products. Ultimately, the 346 results presented here agree with the literature that compost from food waste can be used as a 347 quality plant growth medium (Nguyen et al., 2020).

349 3.11. Economic Practical Evaluation and Future Research Direction

348

350 Household food waste composting does not require labor, transport, sorting, or-351 processing fees. Zhou et al. (2020) believe that the in-situ composting system differs from the 352 centralized composting system. The thermal composter used in this study processed 1 kg of 353 food waste per day, using a total electrical power of 1_,452 kWh-(Fig. 5). This total power 354 consists of the shredding unit (i.e., 0.00375 kWh), the spiral stirring unit (i.e., 0.00828 kWh), 355 and the heating unit (i.e., 1.440 kWh). To process 1 kg of food waste in a day, the heating unit 356 required the most power as it operated for 24 h, while the shredding and stirring units operated 357 for only 30 and 80 s, respectively. The total cost for operating the thermal composter amounted 358 to 2,097.76 IDR to process 1 kg of food waste in a single day. The total cost of the composter 359 developed by Zhou et al. (2020) requires \$0.033 (445.98 IDR) per kg for food waste, but the 360 composting time is longer (four days). Even though the electricity cost is 2,097.76 IDR to 361 process 1 kg of food waste in a day, food waste composting using a thermal composter still get profits from selling the compost product as a fertilizer for 5,000.00 IDR (Paduloh & Rosihan, 362 363 2021). The compost produced from the thermal composter can be used directly as fertilizer,

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CREDIT AUTHOR STATEMENTS

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An innovative thermal composter to accelerate food waste decomposition at the household level



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ABSTRACT

An innovative, portable thermal composter was developed to accelerate the decomposition of food waste at household. The study aimed to evaluate the performance of the composter by assessing the quality of the compost produced. Food waste was chopped, mixed, stirred at 80 rpm, and heated to \sim 55 °C; thereafter, a bulking agent and stimulated microorganisms were added to the mixture. The composter mixing speed was assessed to calculate the feasible composting time. The results revealed that the active phase of composting process could be completed in a day, producing good quality compost. The pH, electric conductivity, and C/N ratio of the compost was 6.72, 1148–1179 μ Scm⁻¹, and 20.38, respectively. The lowest ammonia emissions (i.e., 7.2 g/Nm³) were produced on the sixth day. The total cost required to process 1 kg of food waste in a day was only 2097.76 Indonesian Rupiah (IDR), highlighting the feasibility of this technology.

1. Introduction

Nearly a third of the worldwide food production for human consumption is lost or wasted, accounting for 1.3 billion tons of food per year. The high generation of food waste, representing a global economic loss, which is accounting around \$400 billion per year (Raj et al., 2022). Among various other types of waste, food waste may generate the highest greenhouse gas (GHG) emissions, as it produces an enormous number of contaminants through natural microbial degradation and other indirect processes, including transportation and the use of food processing machinery (Shen et al., 2020). Therefore, preventing food waste at the household level, downstream of the food supply chain, is critical in limiting climate change (Parfitt et al., 2010).

There are several food waste management strategies, including composting (Cesaro et al., 2019), animal feed (Mo et al., 2018), anaerobic/aerobic digestion (Wainaina et al., 2020), gasification, incineration (You et al., 2016), pyrolysis (Kim et al., 2020), and direct landfill disposal (Goodman-Smith et al., 2020). Composting remains the most widespread solution in developing countries, where it treats ~90–96 % of food waste (Thi et al., 2015). Effective food waste management has been proven to reduce pollutants, odors, and GHG emissions (Wei et al., 2017; Zaman et al., 2021). In addition, composting is a common practice that can be easily implemented in residential households.

Composting systems at the household and community level have been discussed by Lu and Sidortsov (2019). Household-level composting equipment allows residents to compost their food waste, ultimately reducing the volume of domestic waste transported to communal waste processing facilities. There are, however, some challenges facing composting systems at the household level. For example, there is the likelihood of odor emissions during the biodegradation process (Zhou et al., 2020). Moreover, the long processing times involved with composting may lead to residents being unwilling to compost in their homes. The success of household-level composting also depends on the knowledge, capacity, and self-awareness of the residents who manage the household's waste (Fadhullah et al., 2022).

There are some techniques presented in previous literatures for reducing the processing time of household composting. For instance, Kalamdhad et al. (2009) created a drum-shaped thermophilic composter consisting of chambers with varying temperatures at its chamber. The thermophilic conditions allow for microbial metabolism activation, accelerating the humification rate. The higher the temperature, the greater the microbiological activity will be (Ottani et al., 2022). Food

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Received 9 July 2022; Received in revised form 20 August 2022; Accepted 21 August 2022 Available online 30 August 2022 2589-014X/© 2022 Elsevier Ltd. All rights reserved. waste composting with the addition of microorganisms and thermal elements (0–100 °C) reached the maximum temperature faster (3 days), and the maturation period decreased (4 weeks) (Charkhestani and Kebria, 2022). The composting time of 4 weeks is still contrary to the community's wishes, where they want the composting process to happen right after they throw the waste away in the composting machine. Awasthi et al. (2017) also found that adding multifunctional microorganisms produced better germination test results and a composting period of 20 days. A recent study reveals that adding biochar can increase the composting temperature and achieve an advanced thermophilic temperature in a short period of time. Thus, making the composting time lasted for only 20 days (Jain et al., 2018). Oktiawan et al. (2018) used a bulking agent at as much as 30 % of the total waste to produce mature and stable compost. A processed food waste size of ± 2 mm is ideal for microbes to carry out the humification process and increase composting efficiency. Therefore, continuous aeration and rotation can also reduce the active phase of composting treatment from several weeks to only 4.5 days (Alkoaik, 2019). Since the processing time has become a limitation for applicability at the household level, some modifications are still required to increase its efficiency and ensure its feasibility as a household composter.

This study developed an innovative household composter with several modifications which fill research gaps and addresses issues presented in previous studies. Furthermore, the composter designed here is simple to use, portable, and operated automatically. Essentially, food waste was stirred, heated, mixed, and decomposed in the composter, allowing active phase of composting to be obtained within a short period. The aim of the study was to demonstrate the utility of a thermal composter prototype in different operational environments. Furthermore, due to the limited research and the importance for further developing food waste management strategies at the household level, the goal of this study was to demonstrate a thermal composter that may accelerate the food waste composting process. The focus here was on compost quality and morphology, ammonia (NH₃) gas emissions, and the total operating cost.

2. Methods

This research was conducted in the greenhouse of the Environmental Engineering Department, Faculty of Engineering, Diponegoro University. The thermal composter (see Fig. 1) was made of stainless steel (Type 316 austenitic, Indonesia) with dimensions of 60 cm \times 30 cm \times 55 cm (length \times width \times height). The composter frame was made of corrosion-resistant galvalume, and its outer layer was made of white and green acrylic. The thermal composter consisted of an inlet chamber, a food waste chopper, a spiral stirrer driven by a motor (0.5 hp, 3-phase,



Fig. 1. Schematic diagram illustrating the design of the thermal composter developed in this study.

1370 rpm, China), and a heater (12 V). The heater was set to \sim 80 °C to accelerate the microbe metabolism and the humification rate. The bottom and sides of the composter were equipped with insulators to reduce heat loss. Finally, activated carbon and a UV lamp were attached to the top of the composter to remove odors and microorganisms resulting from the food waste decomposition (Zhou et al., 2020).

Food waste was collected from a restaurant in Semarang City using trash bags and transported to the Environmental Laboratory, Faculty of Engineering, Diponegoro University for analysis. Prior to starting the experiment, the composition and physical properties of the food waste were determined; thereafter, the food waste was mixed. The bulking agent used here came from mature and stable compost with a size of 100 mesh. The food waste consisted of various and mixed ingredients such as leftover rice, spinach, chayote, banana peels, vegetable gravy, and many more. First, food waste (500 g per day) was added to the composter inlet and chopped until the food waste particle size was homogenized to ~ 2 cm. Thereafter, the bulking agent was added, accounting for as much as 30 % (v/v) of the total food waste. The mixture was then periodically stirred by the spiral stirrer and slowly pushed into the heating chamber, where it was rotated for 1 min every 6 h. Despite the heater being set to 80 °C, the mixture's temperature gradually decreased to 28–30 °C while in the cooling compartment or outlet chamber. The composting cycle was carried out for 7 d by adjusting the rotational speed of the spiral stirrer to 80 rpm. Compost was removed via the outlet chamber, with samples collected daily and stored at 4 °C until further analysis.

Laboratory tests were conducted to ensure that the compost was actively produced. Compost quality was assessed using the following parameters: (a) moisture content (MC), (b) electric conductivity (EC), (c) pH, (d) temperature, (e) total nitrogen (TN), and (f) total organic carbon (TOC). The gravimetric method was used to determine the MC, with the sample being heated to 105 °C using an oven (Memmert UN 50, Germany). The Kjeldahl method was used to determine TN, while TOC was assessed using the Walkley-Black method (UV-Vis 150 Spectrophotometer, Thermo Fisher Scientific, USA). The NH₃ emissions were assessed using the indophenol method and a spectrophotometer (Indonesia National Standard - SNI 19-7119.1-2005). The compost surface morphology was assessed using scanning electron microscopy (SEM) (Phenom ProX Desktop Scanning Electron Microscope, Thermo Fisher Scientific, USA) at a magnification of $100,000 \times$. To do so, 2 g samples of three compost components (i.e., the bulking agent, food waste, and final compost) were collected and oven-dried at 110 °C for 48 h (Memmert, Germany). The sample was ground, sieved through 200 mesh and fixed on a stub (circular metallic plate holder). Thereafter, the sample was sputter coated with gold (Sputter Coater, Quorum Q300T D Plus, UK), ensuring visibility of the morphology.

Plant growth tests were conducted to assess the quality of the compost as a plant growth medium. This was done following the procedure described in Nguyen et al. (2020). Mung bean (Vigna radiata) plants sourced from a farm shop (Semarang, Indonesia) were planted in nine polybags of 5 cm \times 15 cm (width \times height) containing compost samples. All plants were treated equally and received the same daily watering. At 7 d, the plants were removed from the polybags, and several morphological parameters were measured, including height, weight, root length, and the number of leaves. The plant heights were measured using a ruler, plant weights were measured using an analytical balance (Mettler Toledo, Switzerland), and the germination rates were observed daily. The presence of flies and odors was recorded following the methodology described in Lleó et al. (2013). Finally, an economic evaluation was undertaken, aiming to assess the total costs incurred while operating the thermal composter. The total electrical power required for each component of the composter was converted into Indonesian Rupiah (IDR). Components that required electric power were the chopper, heater, spiral stirrer, and UV lamp. Replacement costs of the activated carbon and bulking agent were also calculated in detail. No labor or transportation costs were incurred.

3. Results and discussion

3.1. Moisture content (MC)

The food waste contained an MC of 86.64 % (Table 1); this was much higher than the recommended MC (i.e., 40–60 %) for favorable microbial growth (Guidoni et al., 2018). However, food waste can produce a significant amount of gas and favors anaerobic processes, which in turn can produce foul odors and contribute to the emission of GHGs (Onwosi et al., 2017). The bulking agent contained an MC of 43.16 % (Table 1). Despite this, during the composting process, the MC of the food waste and bulking agent mixture decreased drastically to 32.58 % after 24 h (Table 1); this was due to the chopping, heating, and stirring that took place in the thermal composter. Water in the food waste evaporated during the heating and thermophilic composting process; this resulted in the MC decreasing to 19.76 % at 4 d, while at 5 and 7 d, MCs increased to 23.55 % and 23.89 %, respectively (Table 1).

The microbes almost became inactive after the MC dropped below 20 %; at this stage, the compost products could have been bagged (Zhou et al., 2020). The bulking agent, owing to its compression resistance, helped maintain the porosity and structure of the mixture during composting. Indeed, no leachate was observed, indicating that the addition of the bulking agent influenced the total amount of leachate formed during composting (Guidoni et al., 2018). Finally, the stirring frequency helped maintain the porosity of the mixture and added oxygen to the system.

3.2. pH and temperature

The food waste had an original pH of 6.63, while the bulking agent had a pH of 6.70 (Table 1). The daily addition of food waste did not significantly alter the mixture's pH, with the mixture at 1 and 7 d having pHs of 6.72 and 7.01, respectively. This pH range is ideal for developing bacteria and fungi, thus, contributing to the composting process in producing high-quality and mature compost. Yuan and Zhu (2016) stated that the addition of a bulking agent accelerates the increase in pH. Typically, food waste that undergoes natural decomposition produces an acidic pH due to the formation of organic acid (Guidoni et al., 2018). The pH then begins to increase due to the ammonification of organic matter, where organic nitrogen is transformed into amide and ammoniacal nitrogen. The formation of NH3, an alkaline reaction, also increases the pH. Zhou et al. (2020) found that processing food waste using a composter produced weakly acidic pHs during the initial and cooling stages, while an increase in pH was observed during the heating and thermophilic stages. Ultimately, the changes in pH may be attributable to pH imbalances caused by the microbial metabolic activity. Based on the pH value results, compost produced by the thermal composter could be taken during any of the seven composting process days and be used for agricultural purposes.

The heater of the thermal composter was set to 80 °C, ensuring consistent thermophilic conditions in the heating chamber (Fig. 2). The composting temperature in the heating chamber rose rapidly from

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Compost quality parameters and growth test results.





Fig. 2. Graph illustrating the temperature of the thermal composter heater (dashed line), as well as the compost temperature in the heating (solid line) and outlet chambers (dotted line).

26.3 °C to 52.63 °C within the first 20 min (Fig. 2). Within the same period, however, the composting temperature in the outlet chamber only rose from 26.3 °C to 37.44 °C (Fig. 2). A temperature of 52.63 °C in the heating chamber was beneficial for thermophilic microbial metabolism. At 7 d, the compost temperatures in the heating and outlet chambers were 53.69 °C and 40.69 °C, respectively (Fig. 2), indicating rapid food waste composting in the thermal composter. The thermophilic temperature positively impacts the decomposition rate of food waste so that the composting process can be completed in a day. In addition, this thermophilic temperature decreases food waste's water content, where the initial 86.64 % food wastewater content decreases to 32.58 % (day 1) and 23.89 % (day 7).

3.3. Electric conductivity (EC)

The original food waste and bulking agent EC values were 1591 μ Scm⁻¹ and 3270 μ Scm⁻¹, respectively. The mixture had an EC value of 0.891 μ Scm⁻¹ after being processed for 1 d in the thermal composter. The observed EC value decrease was due to the chopping, heating, and thermophilic decomposition that occurred in the thermal composter. However, the overall EC value during the composting process did not alter significantly and had a range of 1148–1179 μ Scm⁻¹. EC values reflect the salinity of the composting matrix (Onwosi et al., 2017). Furthermore, compost is safe for planting when it displays an EC value <4000 μ Scm⁻¹. In this study, EC values were consistently <2000 μ Scm⁻¹ during the composting process, and thus, had no impact on biological activity (Mujtaba et al., 2021).

3.4. Flies and odor

Flies typically land on food waste soon after its disposal. However, in this study, no flies were observed for 7 d, implying that the food waste and the products of its decomposition did not attract flies. Stirring of the

Parameter	Units	FW	BA	C-1	C-2	C-3	C-4	C-5	C-6	C-7
MC	%	86.64	43.16	32.58	25.00	25.50	19.76	23.55	24.07	23.89
pH	-	6.63	6.70	6.72	6.32	6.49	6.53	6.72	6.27	7.01
EC	μ Scm ⁻¹	1591	3270	891	1148	1124	1435	960	1170	1179
Growth test Height	cm	0	7.8	25.3	24.8	20.8	21.7	0	18.5	12.4
Weight	g	0	0.2403	0.4512	0.5116	0.4413	0.5308	0	0.5061	0.4843
Root length	cm	0	1.5	5.2	4.5	4.4	4.2	0	2.3	1
Leaf	Single leaves	0	2	2	2	2	2	0	2	2

FW, food waste; BA, bulking agent; C-1-C-7, daily composting results (i.e., 7 d).

mixture every 6 h did not affect the number of flies. A previous study found that the capacity of the composter was sufficient to stabilize the organic waste (Blazy et al., 2014). Guidoni et al. (2018) found that flies disappeared after the eleventh day of composting three treatments which varied in their ratio of rice husk to raw fruit and vegetables (i.e., 70:30, 50:50, 30:70; v:v). No strong odor was detected during this study. The bulking agent addition allowed the diffusion of gases and it maintained an aerobic composting process. In addition, bulking agents enhanced the inter-particle voids in the composite pile, thereby increasing the air permeability and regulating the humidity of the compost substrate (Yang et al., 2019).

3.5. NH₃ emissions

Emission of NH₃ varies according to the substrate composition, particle sizes, moisture, oxygen distribution, initial temperature gradients, and the overall process conditions (Onwosi et al., 2017). The first day of the composting process produced an NH₃ emission of 4.1 g/Nm³, with an increase to 9.6 g/Nm³ occurring at 2 d (Fig. 3). This increase was likely due to the addition of food waste; moreover, the increasing trend continued until 7 d, which saw an NH₃ emission of 21.2 g/Nm³ (Fig. 3). The NH₃ concentrations in ambient air ranged from 1.6 to 5.4 g/Nm³, with the lowest concentration (i.e., 1.6 g/Nm³) occurring at 4 d and the highest concentration (i.e., 5.4 g/Nm³) at 6 d (Fig. 3). Overall, the NH₃ concentrations in ambient air did not change significantly (p > 0.05).

3.6. Total organic carbon (TOC)

Higher levels of TOC degradation indicate more stable compost (Sharma et al., 2017). After 1 d in the thermal composter, the TOC of the compost mixture decreased drastically by 75.94 %. The TOC for the remaining days ranged from 77.42 to 79.94 %, lower than the initial TOC level (see Fig. 4). The decrease observed here supports Lalremruati and Devi (2021), who stated that the decomposition of vegetable waste is straightforward, owing to it mostly containing cellulose. Liu et al. (2018) reported a decrease in vegetable waste TOC ranging from 11.4 to 32.1 %, when using sawdust, cow dung, and inoculum for 40 d. Notably, the TOC decrease observed in this study remained stable (i.e., 77.42–79.94 %) throughout the 7-d period, despite the addition of 500 g of food waste per day (Fig. 4). Indeed, these results indicate that the thermal composter is effective in accelerating the degradation of TOC, owing to the integration of the mixing system, heating parameters, and bulking agent.

3.7. Total nitrogen (TN)

25.0

20.0

(15.0 NH³ (g/Nm³) (g/N

5.0

0.0 L 0

The initial TN value decreased significantly at 2 and 3 d of the

Ambien

3

2



4

Time (d)



Fig. 4. Graph illustrating the level of total organic carbon (TOC) in food waste during seven days of composting using a thermal composter.

composting process. The decrease in TN is caused by the evaporation of ammonia, and lower pH results in less organic matter mineralization (Wang et al., 2017). As it may see in Fig. 3, the ammonia emission increased from 9.6 to 14.6 g/Nm³. Therefore, the pH values for 2 and 3 d remain at 6.32 and 6.49, respectively, which are lesser than the pH at 1, 4, 5, and 7 d. Indeed, several studies have attributed the decrease in TN to the volatilization of NH₃, when temperature and pH were >45 $^{\circ}$ C (Cáceres et al., 2018; Zhou et al., 2018). Nguyen et al. (2020) found that TN was influenced by temperature; in addition, the optimal TN was found in experiments that were rotated once per day and exhibited a C/ N ratio of 20. Regarding the production of compost from domestic organic waste (Indonesia National Standard - SNI 19-7030-2004), the optimal TN for compost is a minimum of 0.40 %. Indeed, the results obtained here confirm that the TN content in the compost collected at 1, 4, 6, and 7 d meet this quality standard. The highest TN content (i.e., 0.49 %) was found on the first day, while the lowest TN content (i.e., 0.28 %), which does not meet the quality standard, was found at 3 d. Ultimately, temperature and the composition of the compost raw material can affect the TN in the compost.

3.8. C/N ratio

The C/N ratio is a conventional parameter used to assess the composting process (Zhou et al., 2018). The reduction of the C/N ratio due to the simultaneous consumption of carbon and nitrogen organic substrates indicates an effective composting process (Wang et al., 2016), with composts that display a C/N ratio < 20 being considered mature. According to the Ministry of Agriculture of Indonesia Number: 28/Permentan/SR.30/5/2009, organic and biological fertilizers, as well as soil enhancers, typically exhibit C/N ratios within the range of 15-25. The composting process in this study was 500 g of food waste being used as the initial compost raw material; on each of the ensuing days, an additional 500 g of food waste with a typical composition was added. The results reveal that the food waste at 2, 3, and 5 d had C/N ratios >25, ultimately displaying poor composting conditions; whereas at 1, 4, 6, and 7 d, the C/N ratios ranged from 20 to 25, indicating good compositions. The C/N ratio variation found in this study was ultimately driven by differences in the daily food waste composition and quantity.

3.9. SEM images

SEM was used as an additional technique to assess micro-changes in the surface morphology of different compost components (see Fig. 5). In SEM, a focused high-energy electron beam is used to scan the surface of a specimen (Oniguez et al., 2011). The resulting high-quality images provide information about the sample's external morphology (texture) and crystalline structure. Micrographs of food waste samples, compost,



Fig. 5. Surface morphology of (a) bulking agent, (b) food waste, and (c) compost produced from thermal composter at $10,000 \times$ magnification. The red arrows indicate the distribution of particle sizes and the circles indicate the pore diameters. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and the bulking agent as provided in Fig. 5 reveal different particle sizes and distributions per unit area, as well as heterogeneity in particle compaction. Moreover, micrographs showed that the compost sample exhibited larger pore diameters and had no particle compaction. However, while the initial food waste displayed small pore diameters, particle compaction was present. Biodegradation has been shown to lead to improved texture and particle compaction (Arora and Kaur, 2019). The same result was shown by Ajmal et al. (2021), where the food waste has tightened microscopic structure compared to the compost product. This result may be due to the microorganism activity, which reduces the particle size and increase the holes of the fermented food waste. Moreover, the surface roughness and irregular pore shapes shown in the compost product may indicate the possibility of microbial degradation during the composting process (Ma et al., 2022).

3.10. Growth test

Compost products derived from food waste generally provide improved plant growth conditions. The plant growth tests revealed rapid and consistent daily mung bean growth. Growth tests using compost taken from six of the seven composting days (i.e., 1–4, 6, and 7 d) as well as the bulking agent alone, resulted in increased plant height and weight (Table 1). Growth tests using the fresh food waste alone, however, did not facilitate any plant growth, with the waste beginning to rot at 1 d. Moreover, no plant growth was observed t 5 d; this was due to the accumulation of acidic decomposition products. Ultimately, the results presented here agree with the literature that compost from food waste can be used as a plant growth medium (Nguyen et al., 2020).

3.11. Practical evaluation and future research direction

Household food waste composting does not require labor, transport, sorting, or processing fees. Zhou et al. (2020) believe that the in-situ composting system differs from the centralized composting system. The thermal composter used in this study processed 1 kg of food waste per day, using a total electrical power of 1.452 kWh. This total power consists of the shredding unit (i.e., 0.00375 kWh), the spiral stirring unit (i.e., 0.00828 kWh), and the heating unit (i.e., 1.440 kWh). To process 1 kg of food waste in a day, the heating unit required the most power as it operated for 24 h, while the shredding and stirring units operated for only 30 and 80 s, respectively. The total cost for operating the thermal composter amounted to 2097.76 IDR to process 1 kg of food waste in a single day. The total cost of the composter developed by Zhou et al. (2020) requires \$0.033 (445.98 IDR) per kg for food waste, but the composting time is longer (four days). Even though the electricity cost is

2097.76 IDR to process 1 kg of food waste in a day, food waste composting using a thermal composter still get profits from selling the compost product as a fertilizer for 5000.00 IDR (Paduloh et al., 2022). Moreover, the compost improves soil quality, assists the remediation of contaminated soil and reduces the need for chemical fertilizers. Solar cells can be an alternative AC power source for thermal composter operations. In addition, it is necessary to increase public acceptance of the thermal composter so that they can use it to treat food waste.

4. Conclusion

Thermal composting is considered a straightforward and effective strategy to manage household food waste. In this study, an innovative household thermal composter was developed and its feasibility assessed. Active phase of composting was finished after a single day of treatment, with MC, pH, temperature, EC, TOC, TN, C/N ratios, and SEM images meeting the criteria required for high quality compost. Regardless, the compost obtained after a single day was used successfully as a plant growth medium, confirming the compost's low toxicity level. Furthermore, the composter was shown to require a small amount of daily electricity to process food waste.

CRediT authorship contribution statement

Badrus Zaman: Conceptualization, Supervision, Writing – review & editing. Nurandani Hardyanti: Validation, Resources, Software. Purwono: Investigation, Formal analysis, Project administration. Bimastyaji Surya Ramadan: Writing – review & editing, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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